

Studying Nucleon Structure with an Electron-Ion Collider

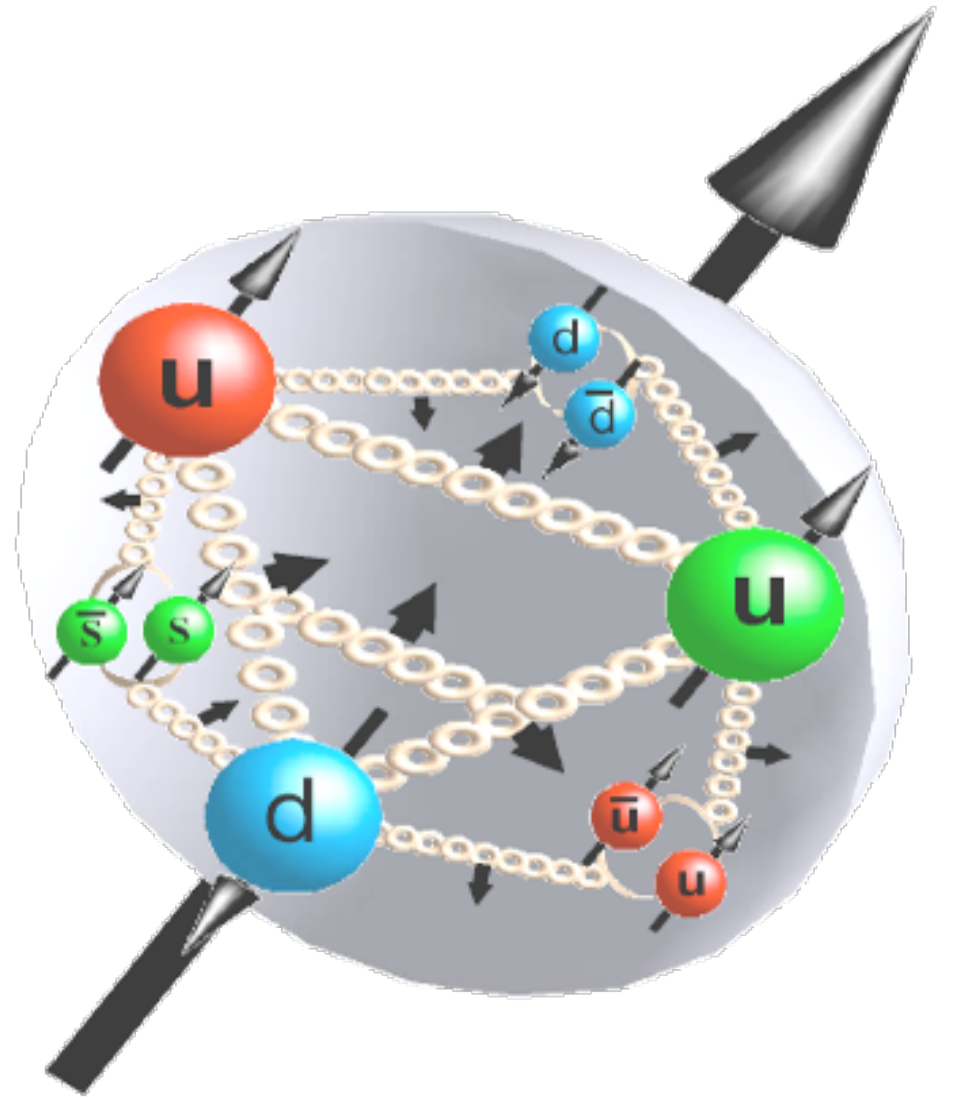


BROOKHAVEN
NATIONAL LABORATORY

Thomas Burton
APS April meeting 2011
Monday 2nd May 2011

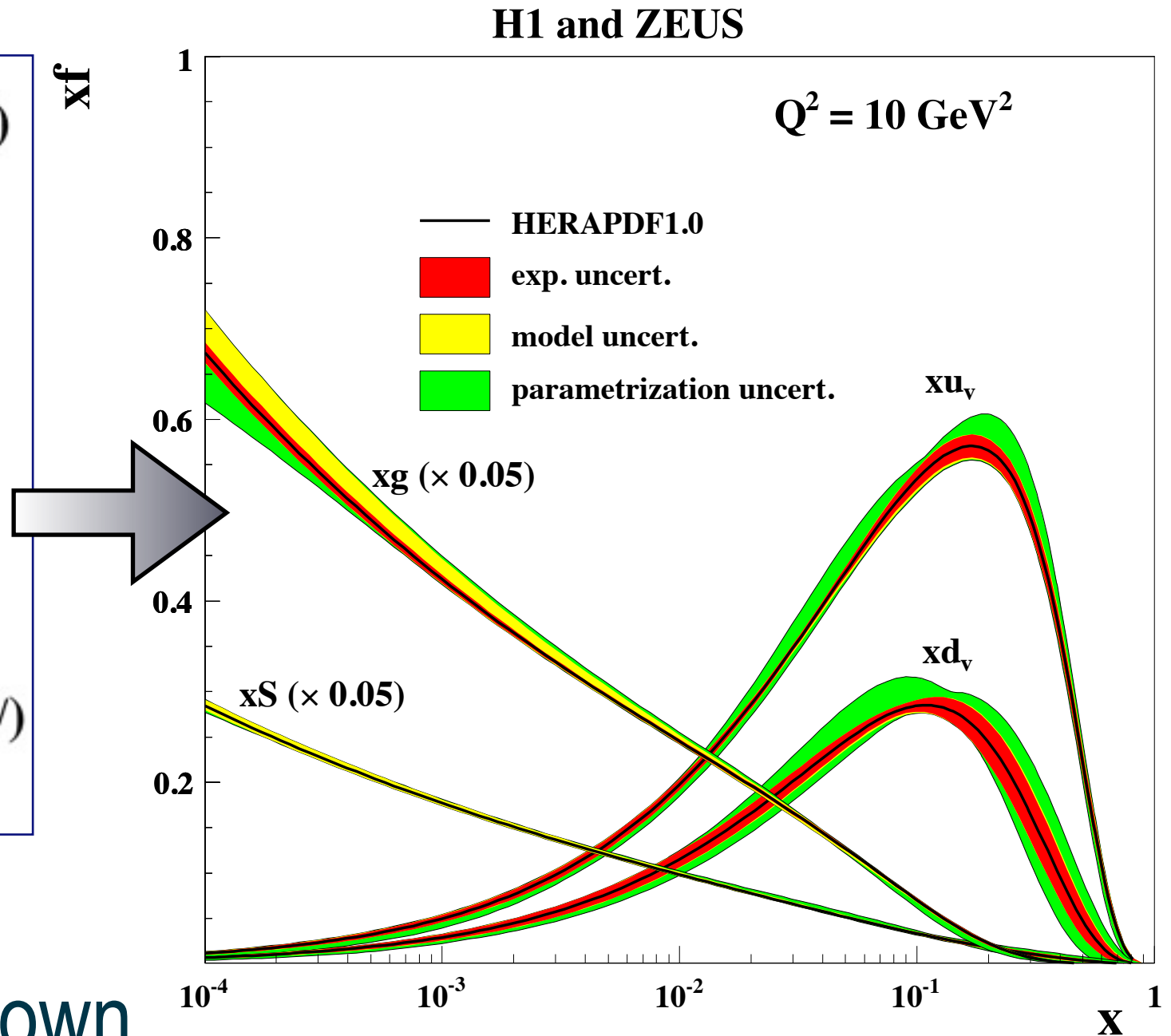
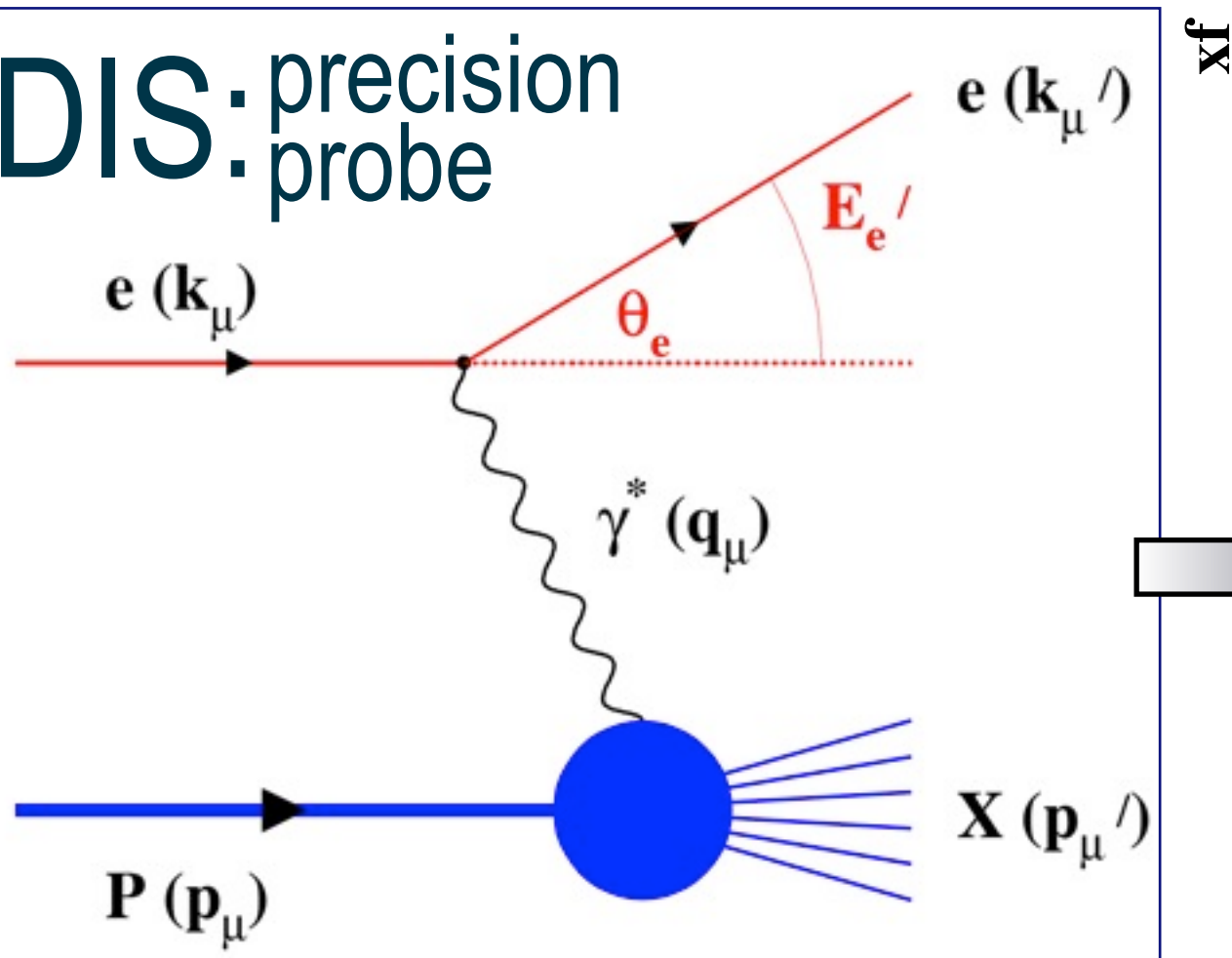
Overview

- What do we know now?
➡ What is still missing?
- What is the Electron-Ion Collider?
➡ How will it provide the answers?
- *A couple of highlights from a huge programme*



Parton distributions

DIS: precision probe



- 1D (x) distribution well-known

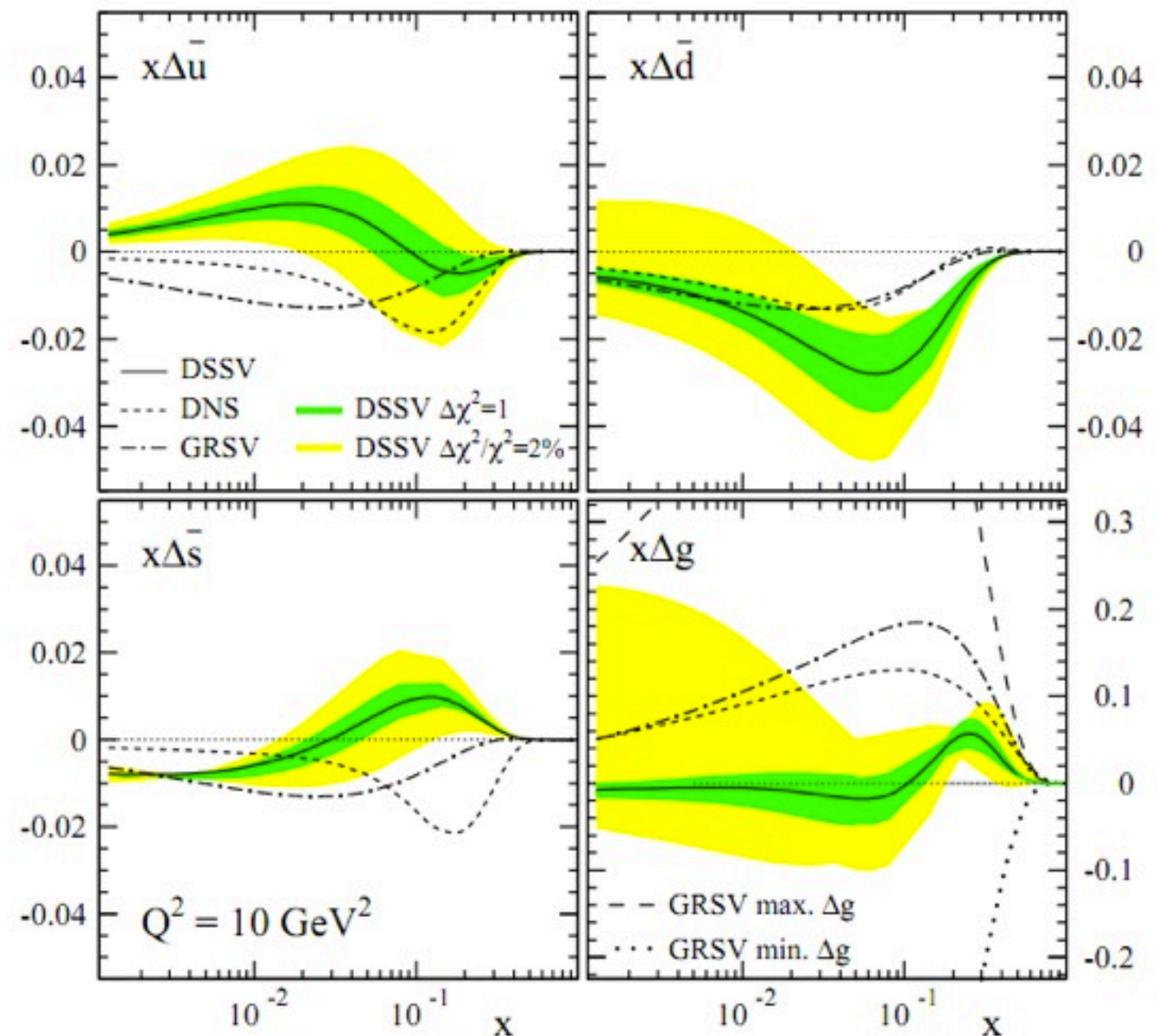
➡ What is the **3D** structure?

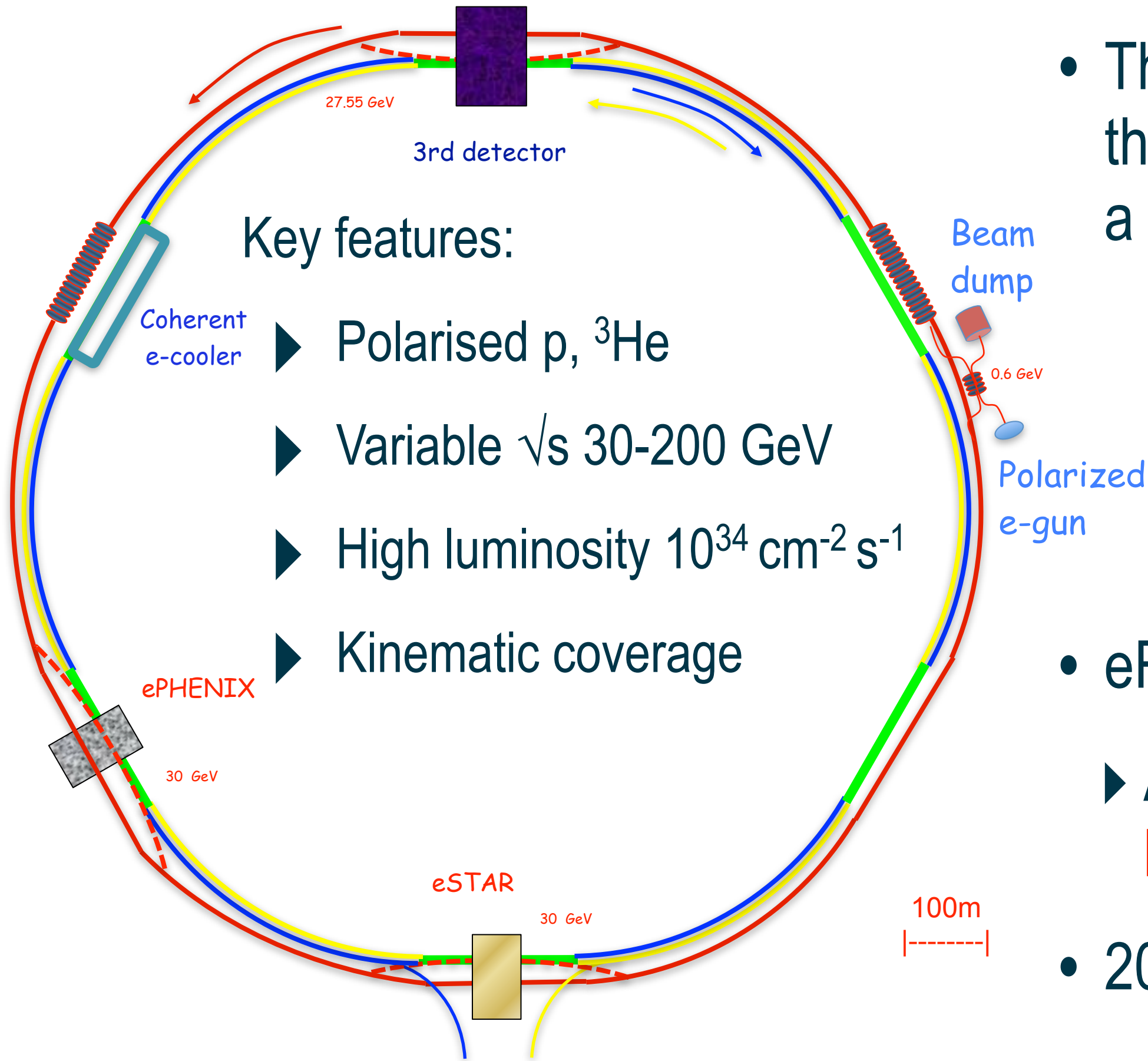
Nucleon spin

$$\frac{1}{2} = \underbrace{S_q}_{\text{30\% small?}} + \underbrace{S_g}_{\text{?}} + \underbrace{L_q + L_g}_{\text{?}}$$

- Gluons?
- Sea quark flavours?
 - ➡ Need data at **small x**
- Orbital momentum?

$$\Delta f \equiv \text{[Diagram: Two red spheres with arrows indicating spin and momentum transfer]} \rightarrow - \text{[Diagram: Two red spheres with arrows indicating spin and momentum transfer]}$$





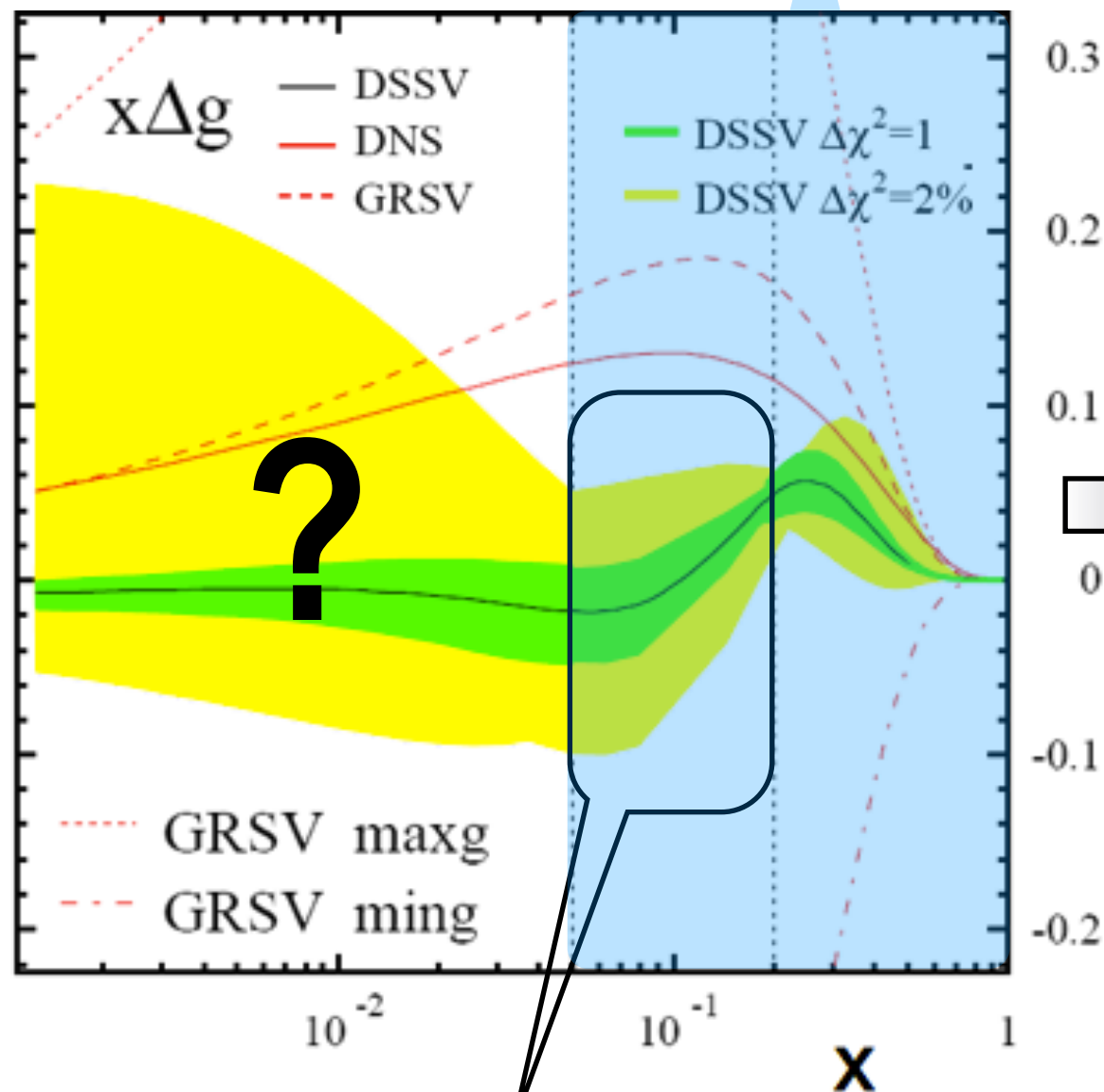
- The answer to these questions: a new facility

Electron-Ion Collider

- eRHIC @ BNL
 - ▶ Adds **electron beam** to RHIC
- 2020+

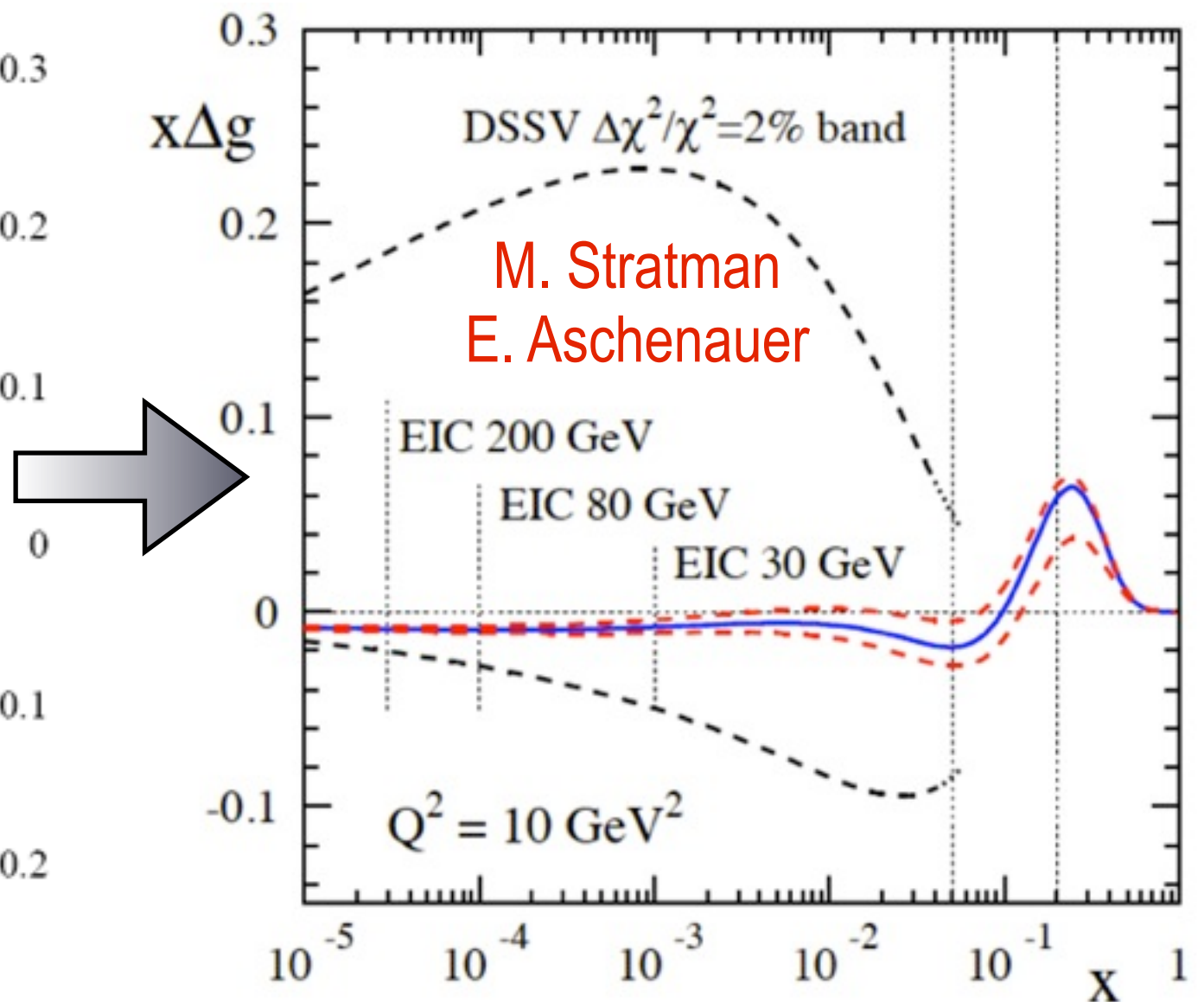
Gluon spin

DIS + RHIC pp data



$$\int_{0.05}^{0.2} \Delta g(x, Q^2) dx \approx 0$$

EIC simulated data



$$S_g = \int_0^1 \Delta g(x, Q^2) dx = \dots?$$

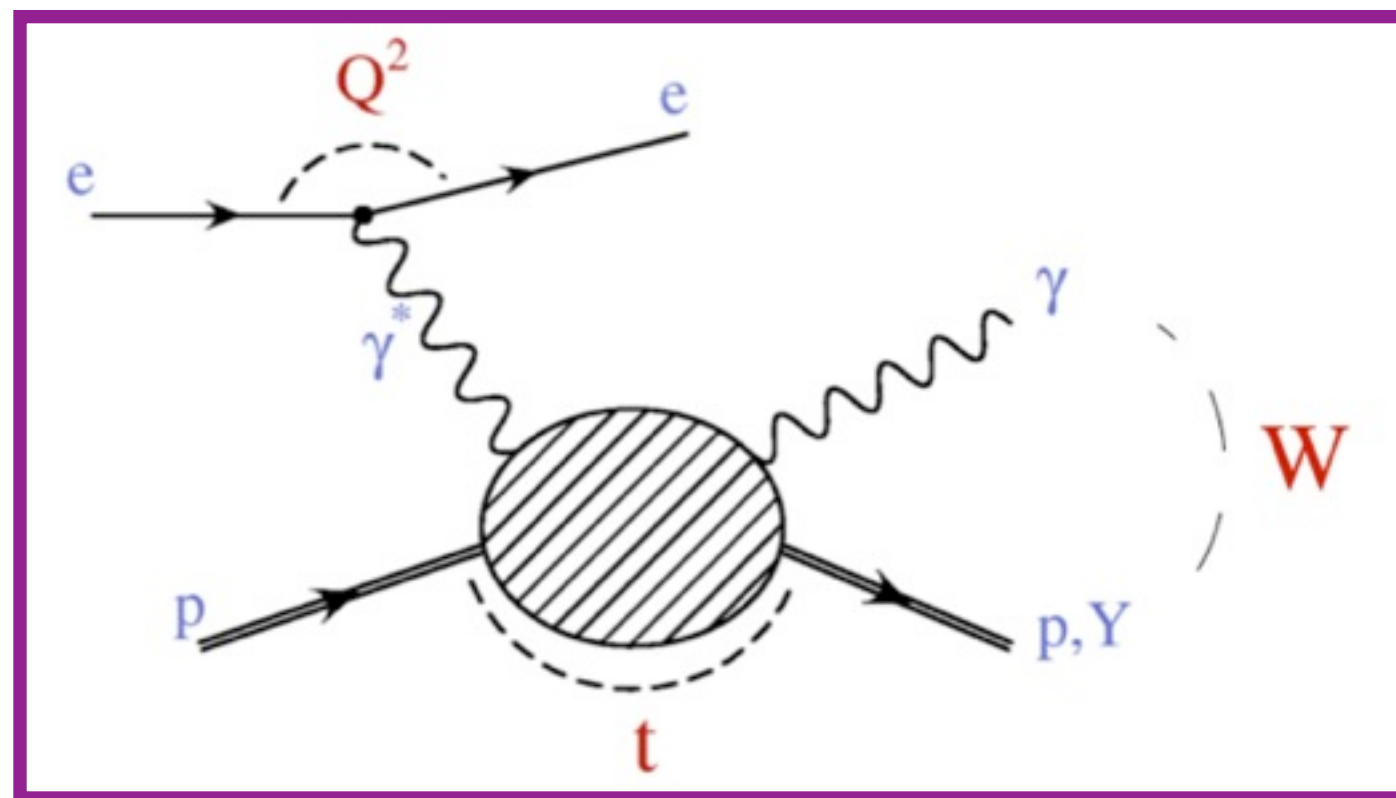
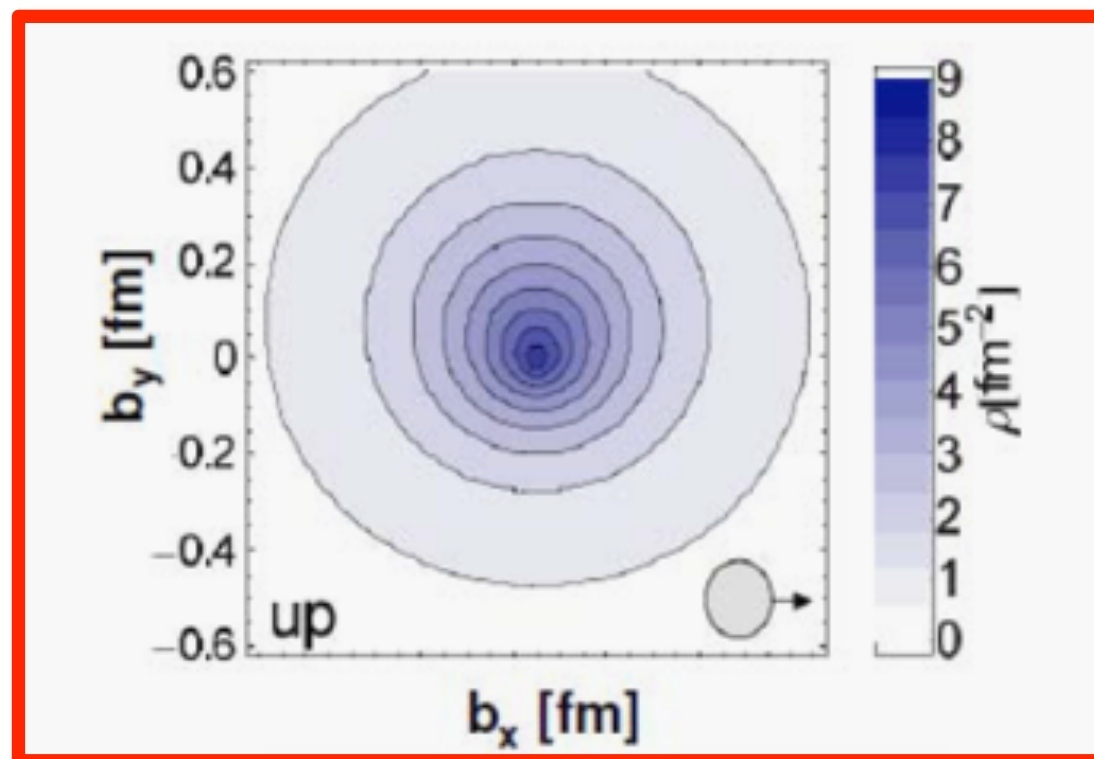
3D imaging

Access **transverse spatial distribution** of partons...

... via **generalised parton distribution functions (GPDs)**...

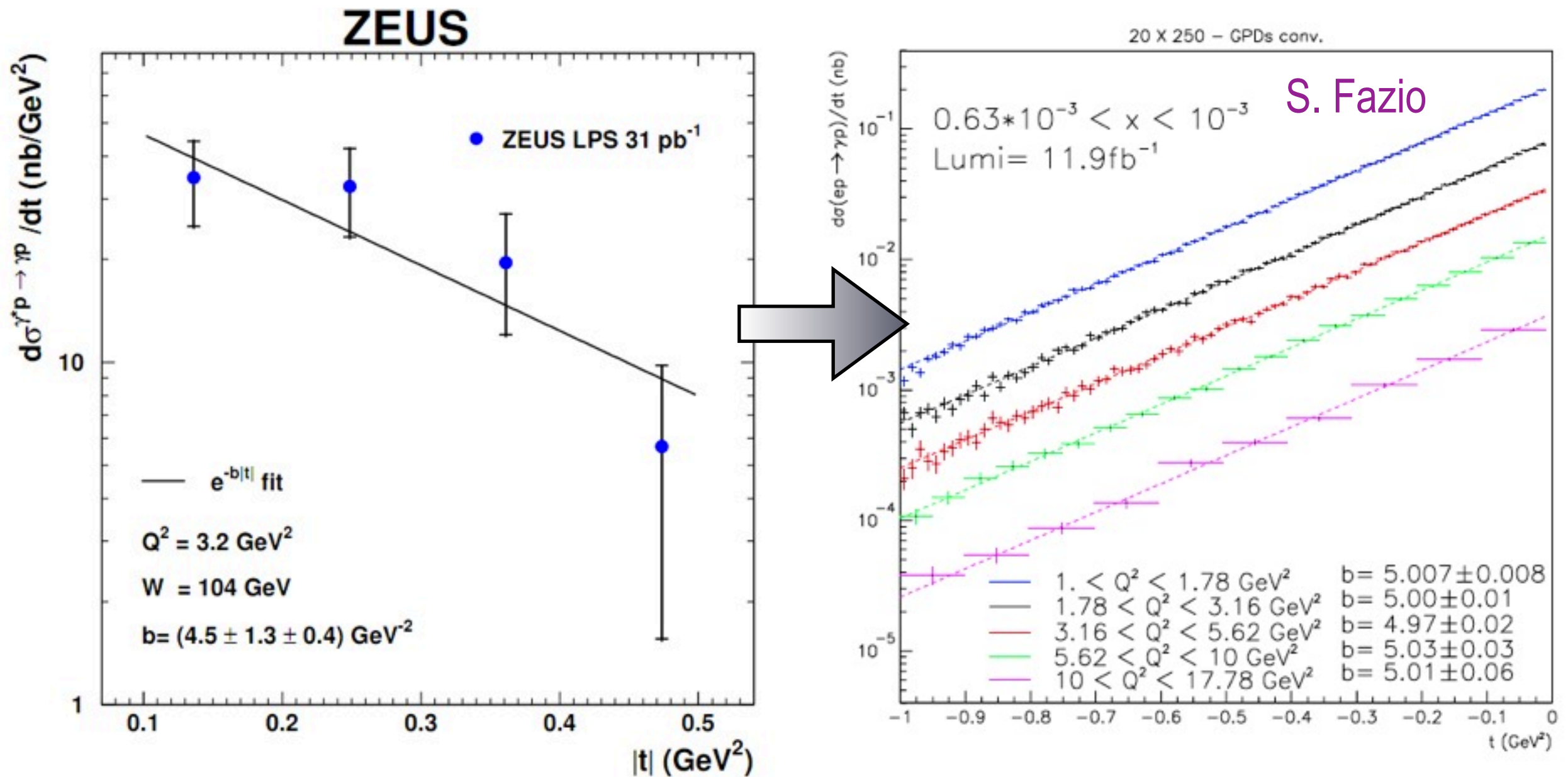
$$\begin{array}{l} H(x, \xi, t) \\ E(x, \xi, t) \\ \tilde{H}(x, \xi, t) \\ \tilde{E}(x, \xi, t) \end{array}$$

...measurable in **deeply virtual Compton scattering (DVCS)**



DVCS cross section

EIC simulated data



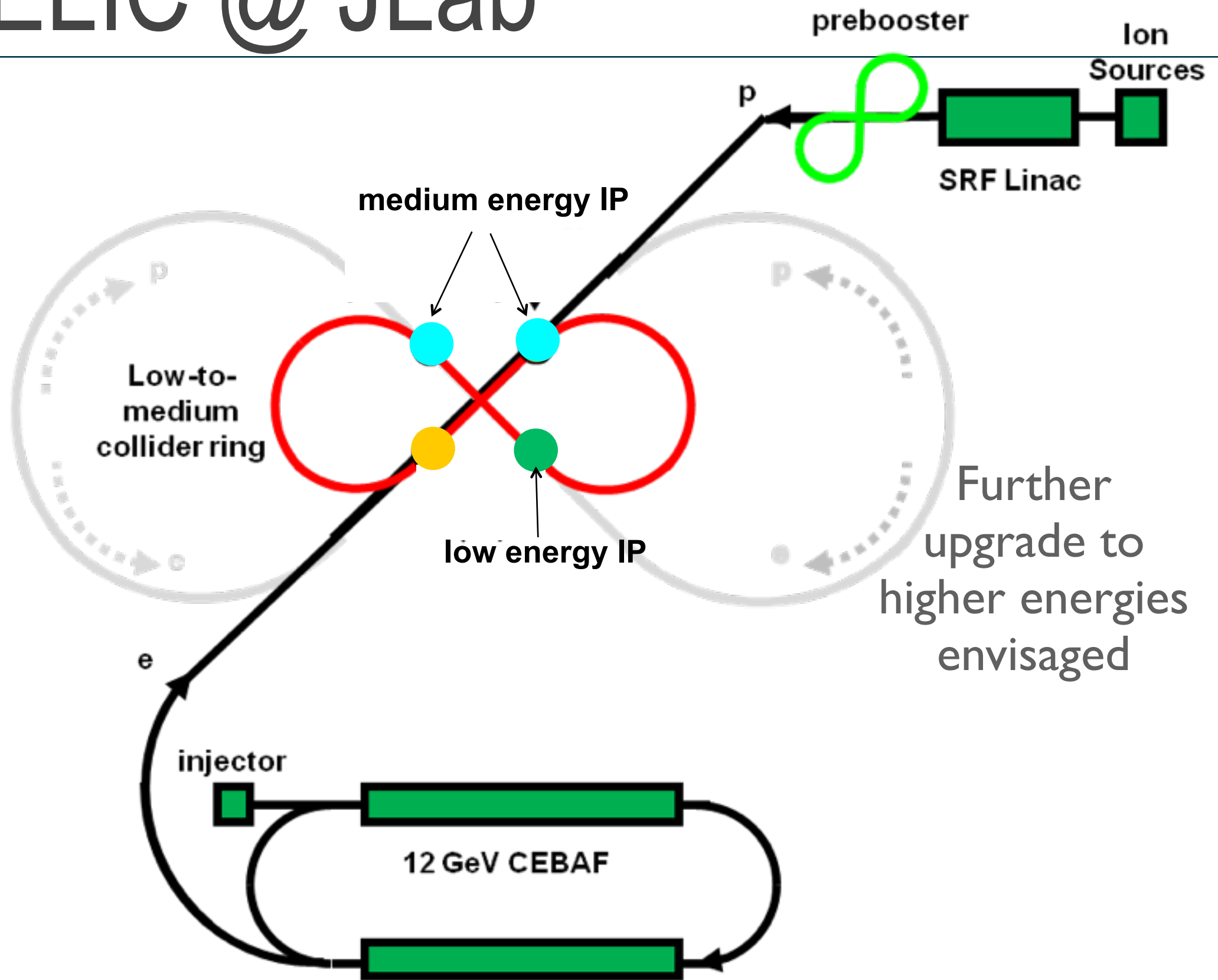
Wide kinematic coverage, great precision
 ➡ Very precise measurement of GPDs

Summary

- EIC combines unprecedented
 - ▶ luminosity
 - ▶ kinematic span
- Delivers **huge** programme of $e + p$ physics
 - ▶ This talk briefly scratches the surface
- See talk by Matt Lamont for $e + A$ perspective (instrumentation I)

Additional

ELIC @ JLab



Comparison

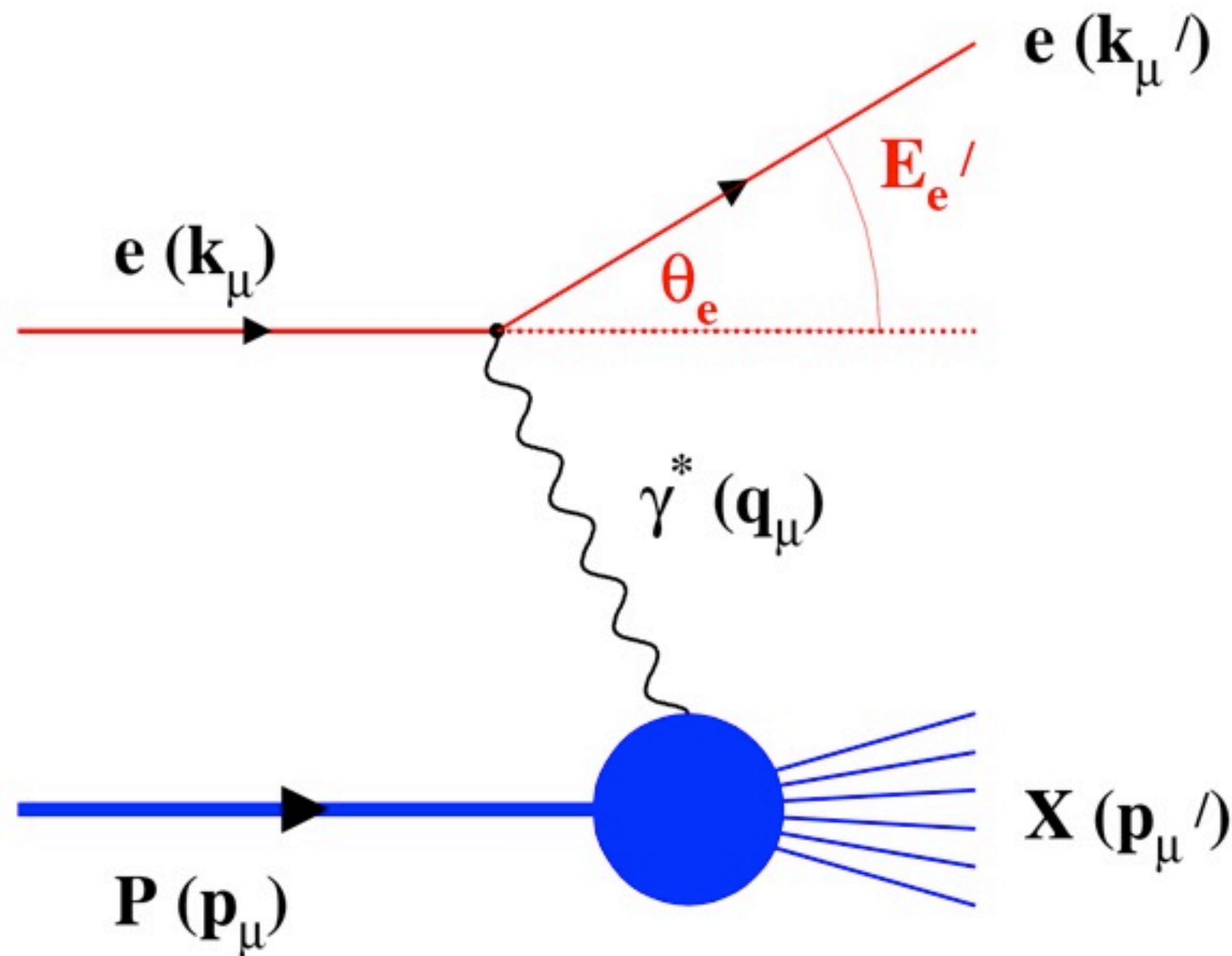
	eRHIC	ELIC
E_{electron}	5 (30)	3 to 11 (20)
E_{proton}	50 to 325	20 to 100 (250)
\sqrt{s}_{ep}	31 to 81 (197)	15 to 66 (141)
E_{ion}	$\rightarrow 130/u$	12 to 40/u (100/u)
\sqrt{s}_{eA}	$\rightarrow 51/u$ (125/u)	12 to 42/u (89/u)
A	p to U	p to Pb

- electron polarisation ~ 80%
- proton polarisation ~ 70%
- $L \sim 10^{33}\text{-}10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

(future upgrades)

Shared features/
requirements

DIS kinematics



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E_e' \sin^2\left(\frac{\theta_e'}{2}\right)$$

“Resolution”

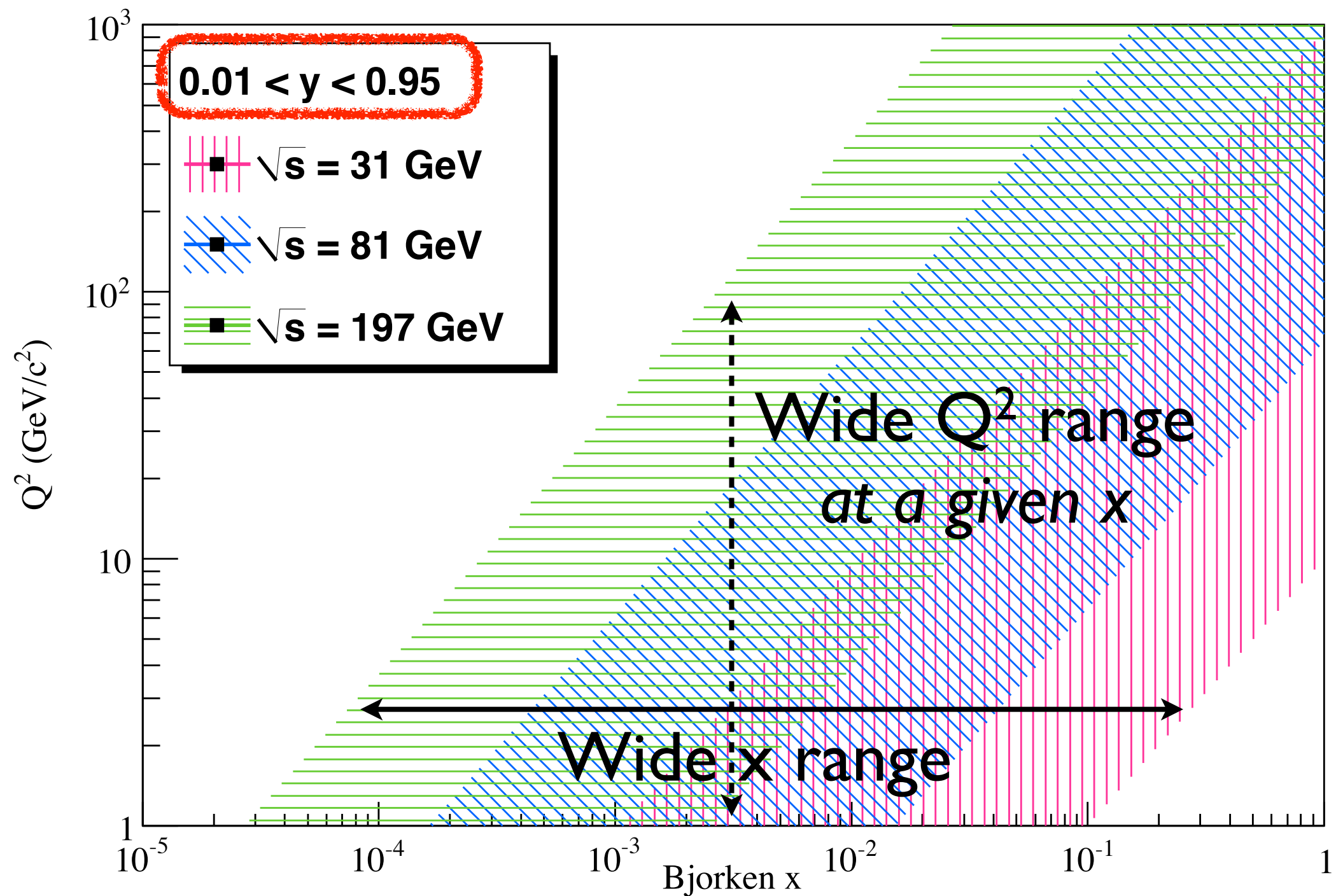
$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e} \cos^2\left(\frac{\theta_e'}{2}\right)$$

“Inelasticity”

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

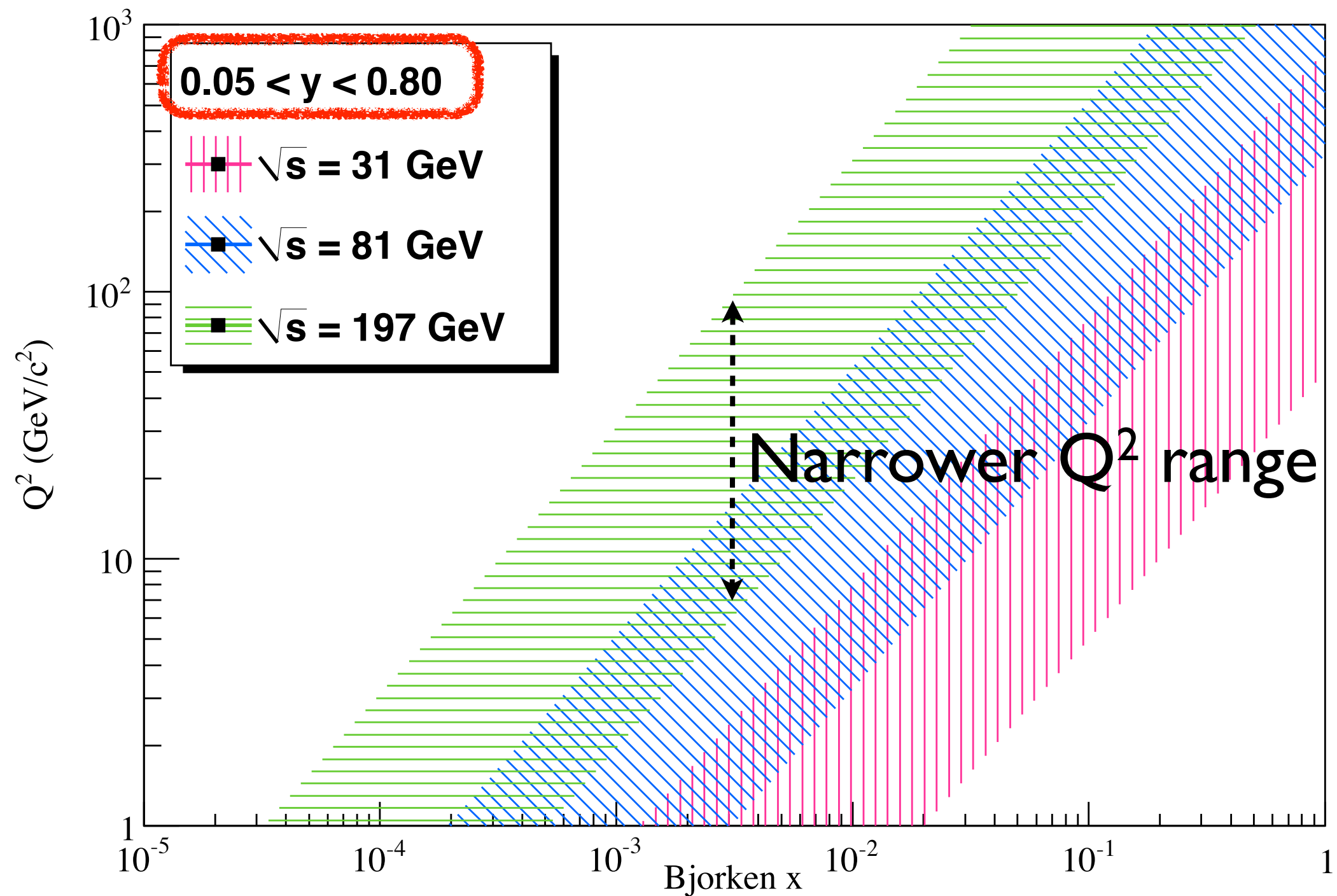
“Momentum fraction”

Q^2 vs. x

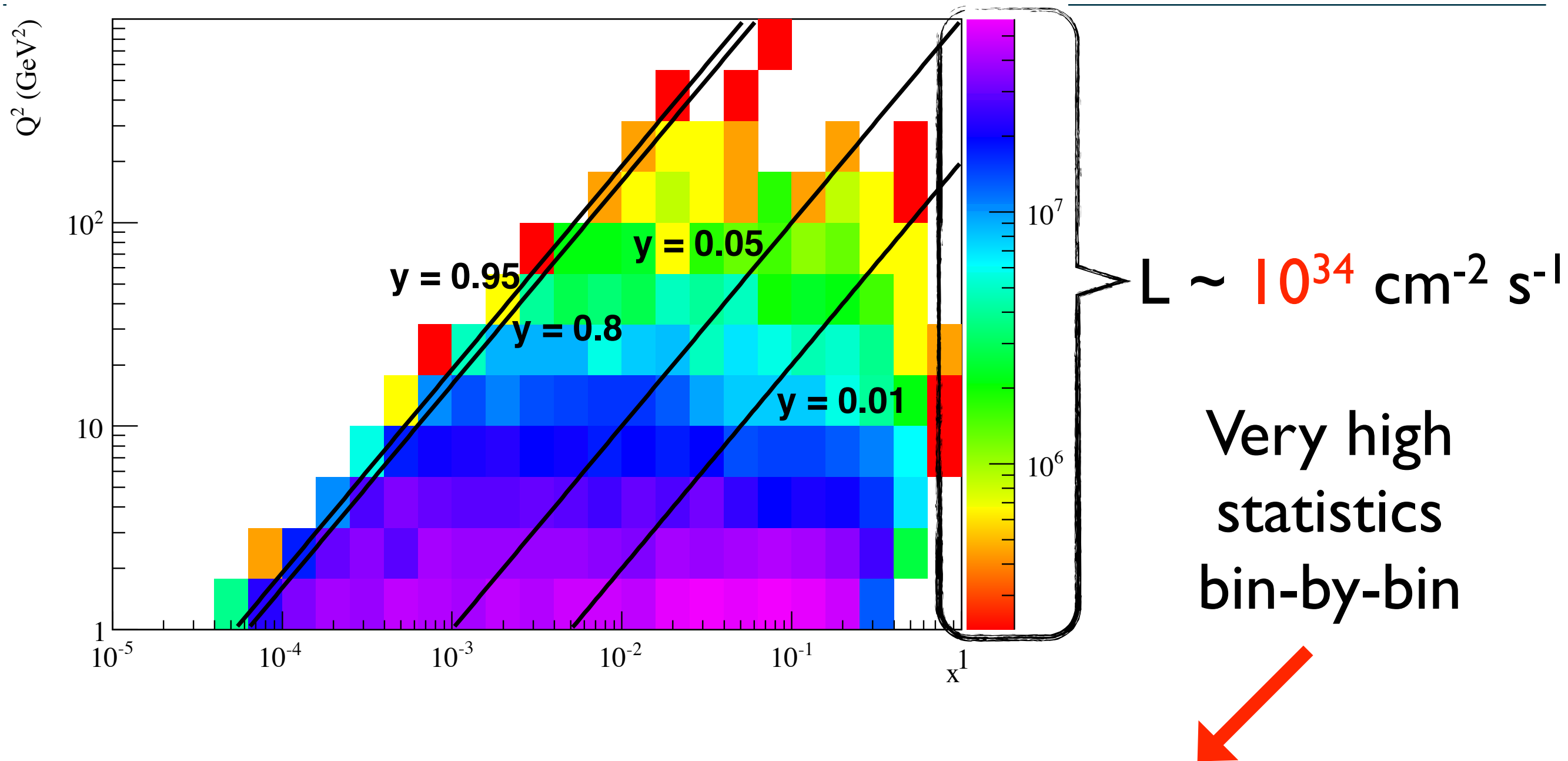


→ HERA has reconstructed down to **$y = 0.005$**

Desire wide y range

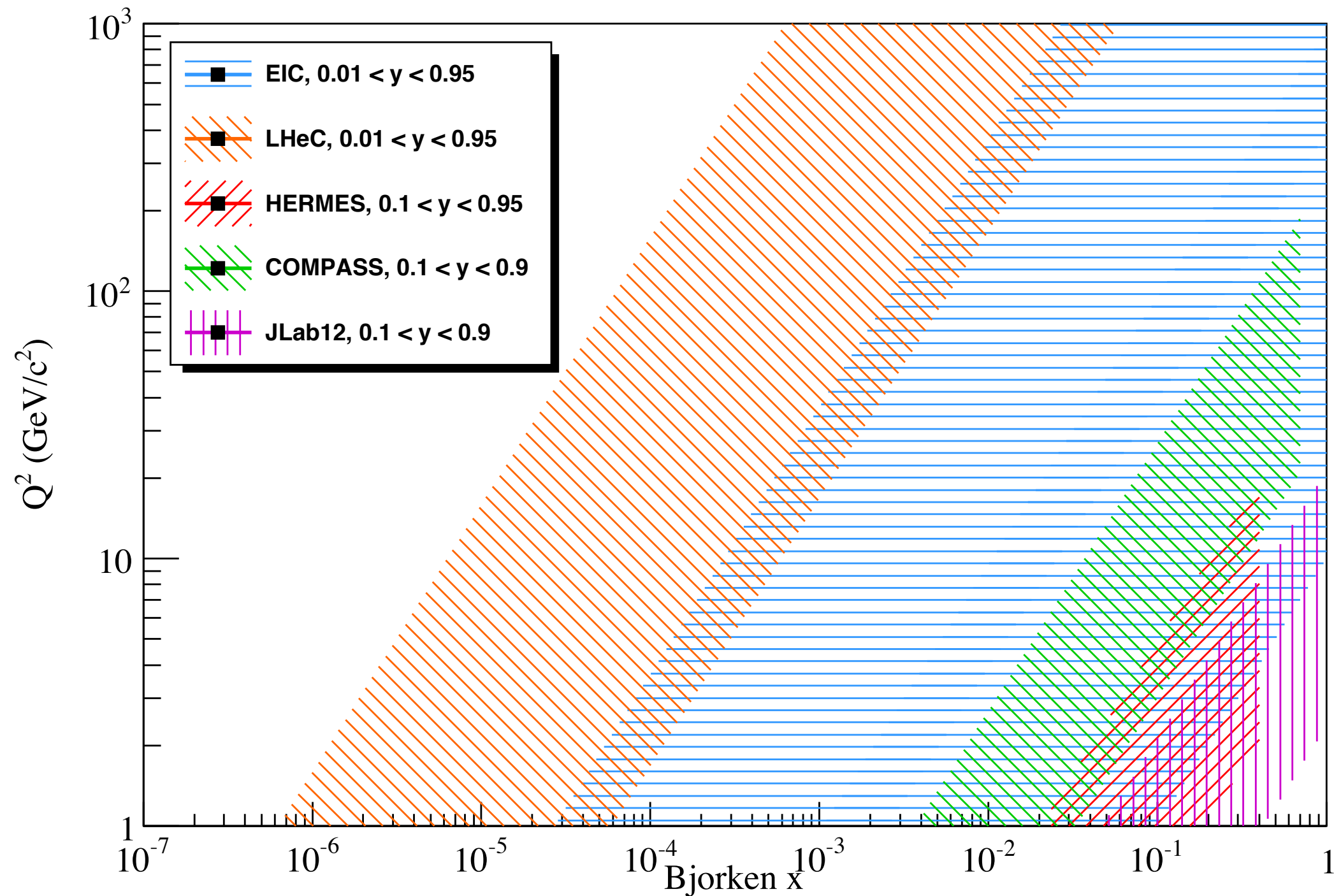


Q^2 vs. Bjorken x , 4 fb^{-1} at $20 \times 250 \text{ GeV}$



- Statistics-hungry measurements can be made
- Inclusive measurements rapidly systematics-dominated

Complementarity



(@ 60 GeV e^- , 7 TeV p)

Longitudinal structure function: F_L

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

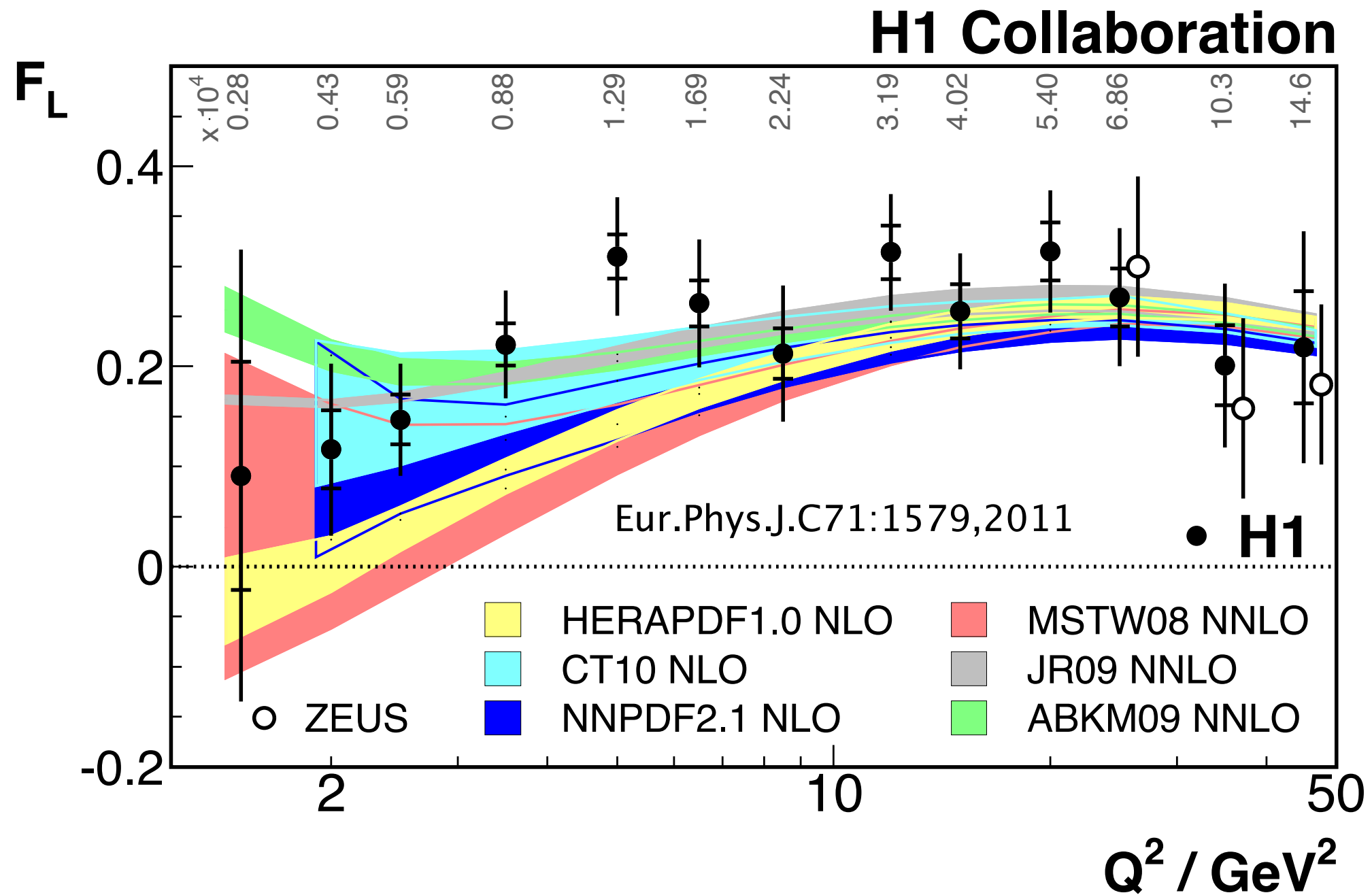
$$Y_+ = 1 + (1 - y)^2$$

- Contributes significantly only at large y
- Use **variable s** at fixed x , Q^2
 - ▶ σ_r slope vs. y^2/Y_+ $\Rightarrow F_L$
- EIC strength
 - ▶ e.g. eRHIC $\sqrt{s} = 30\text{-}200$ GeV

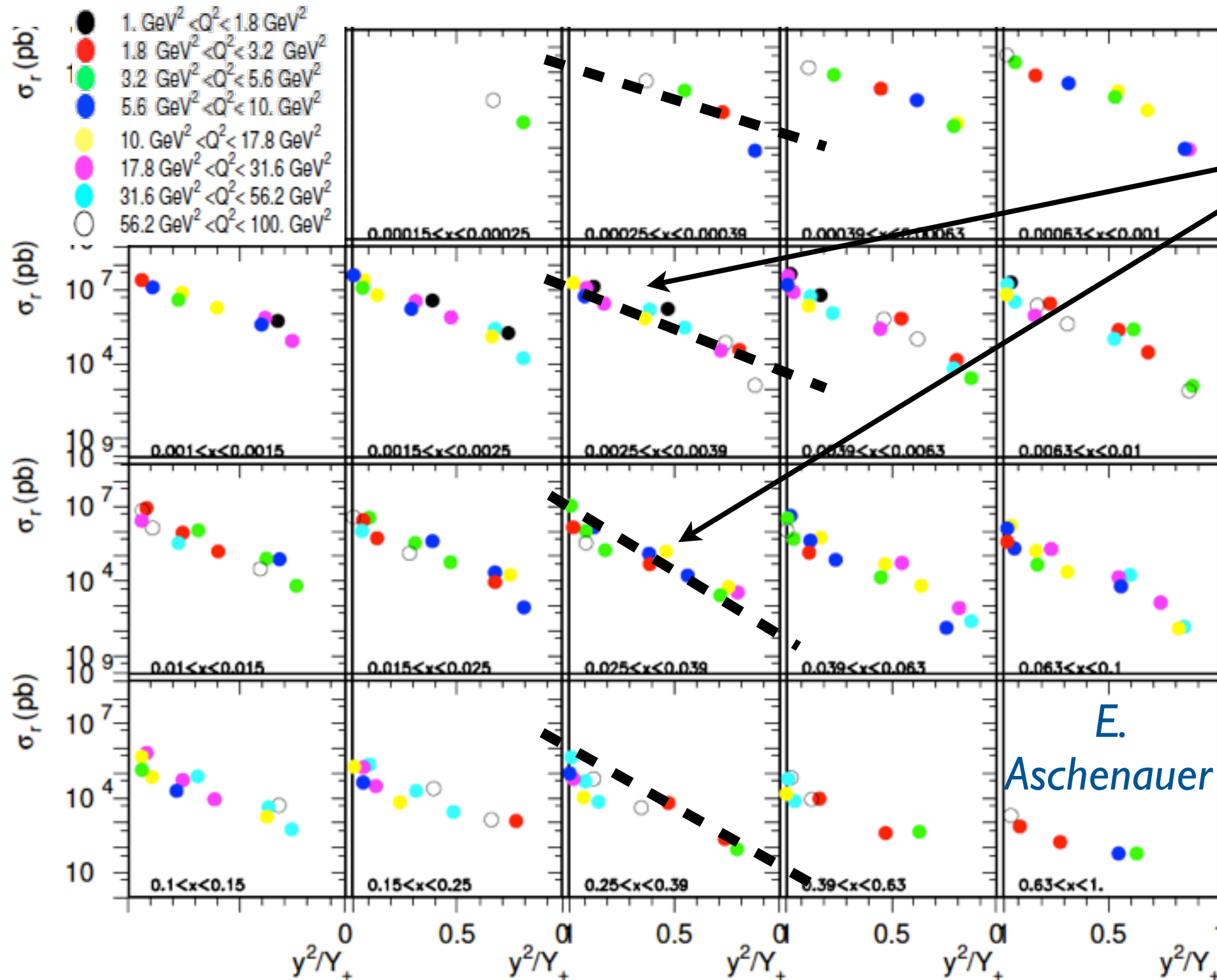
$$Q^2 = sxy$$

F_L

- Measured at HERA, but precision limited



Feasibility study



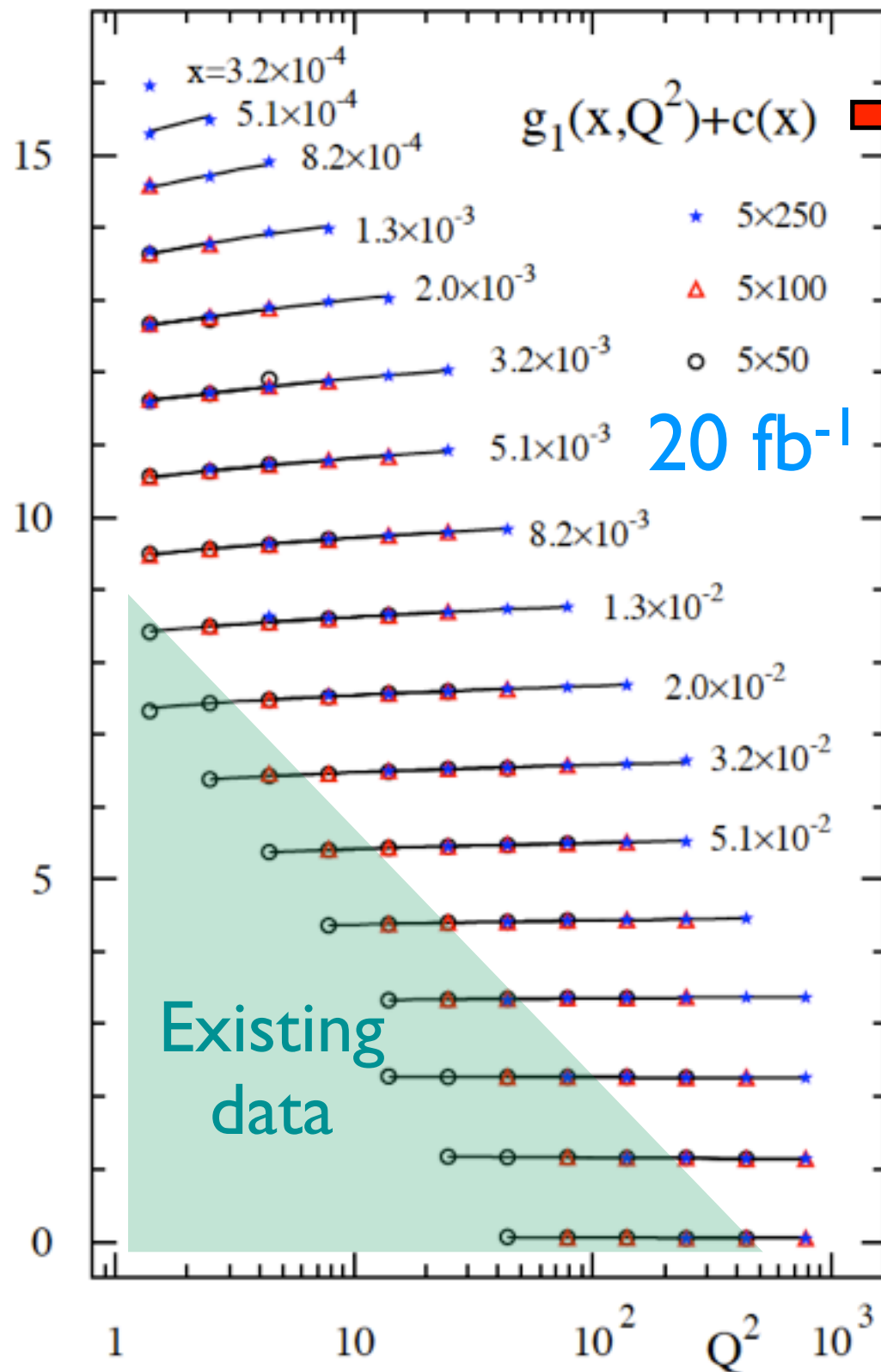
Measure
slopes

Statistical
uncertainties
smaller than
points

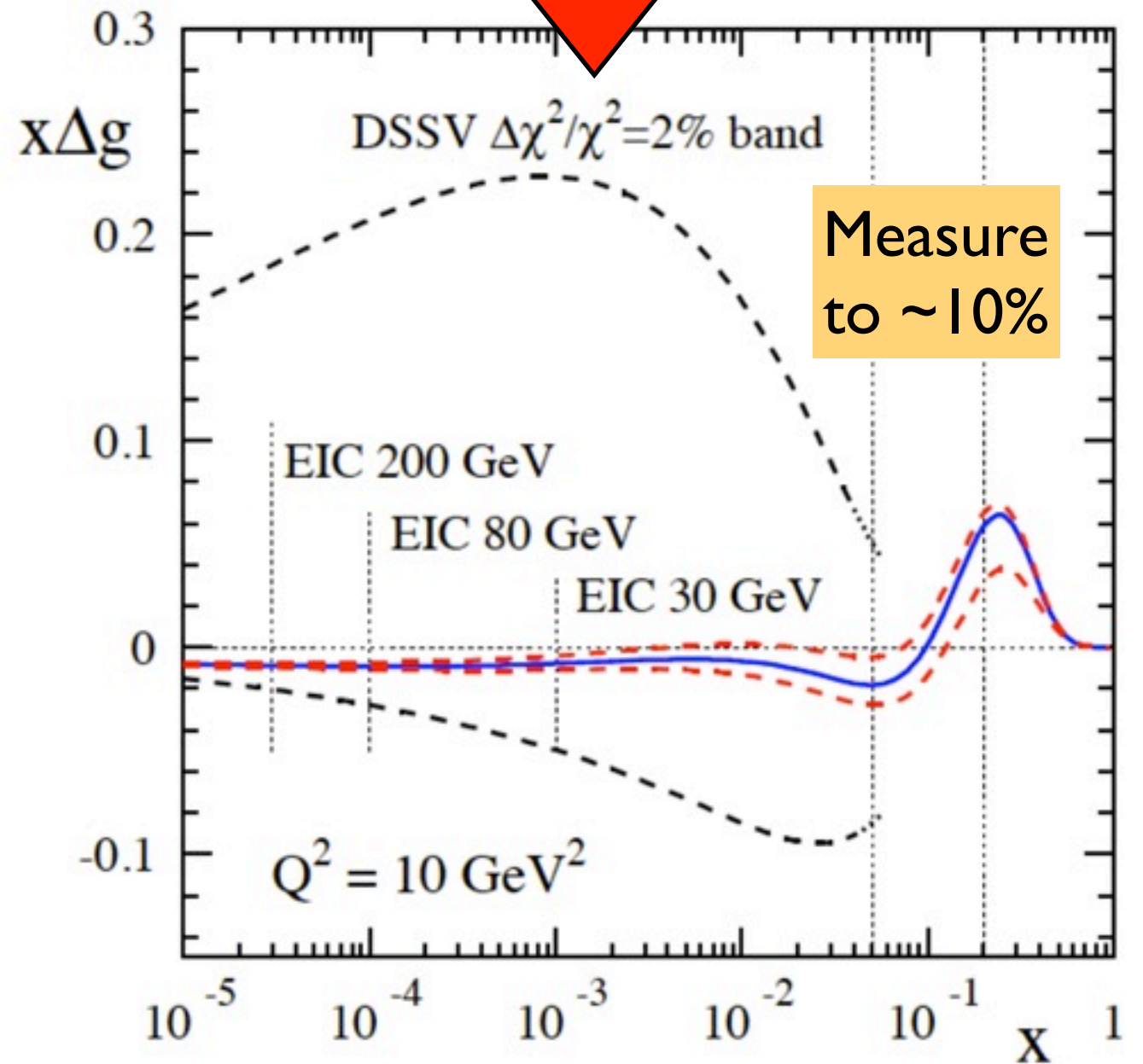
Under
refinement -
how well can
we do?

$$Y_+ = 1 + (1 - y)^2$$

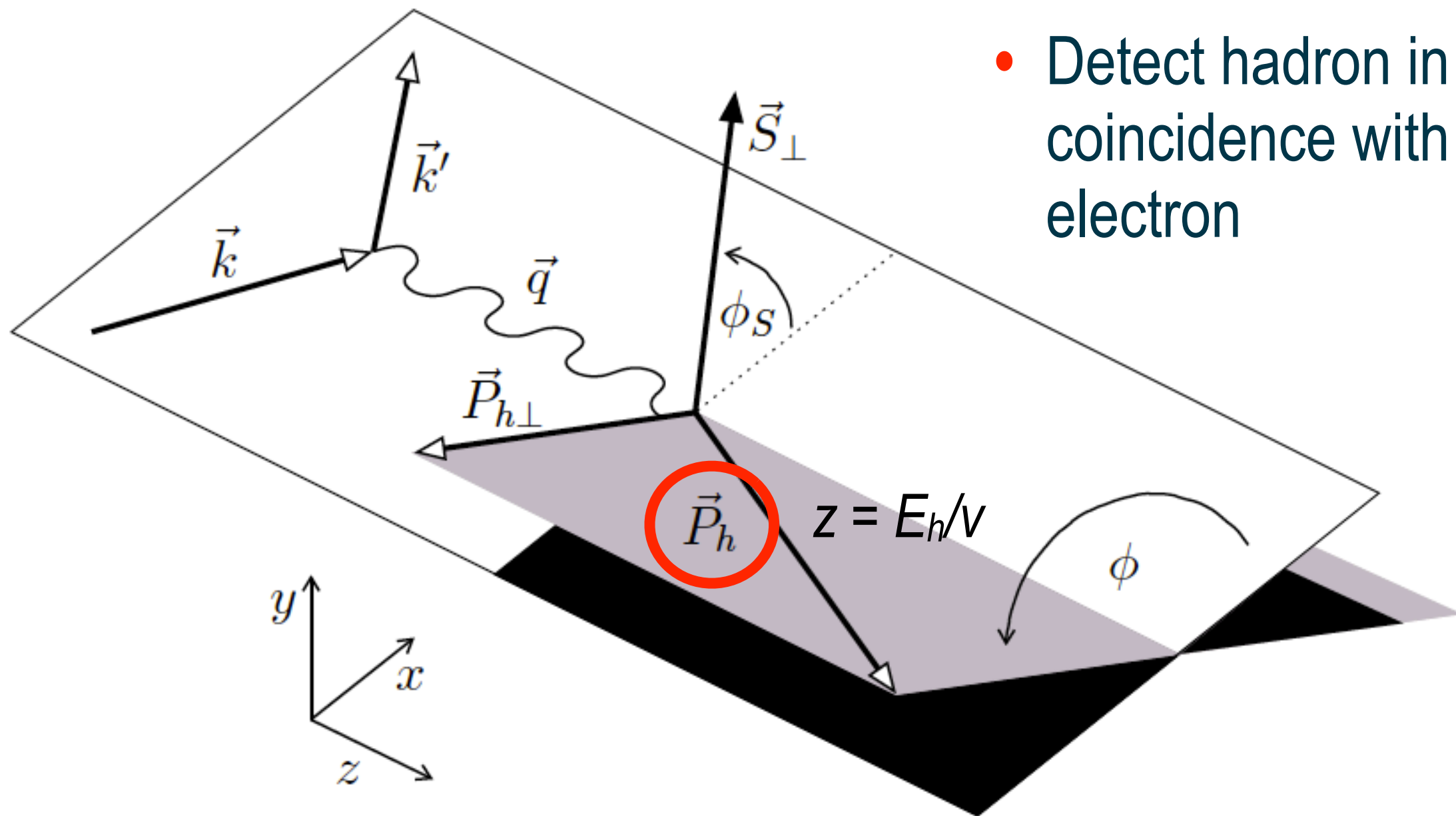
Pseudodata study



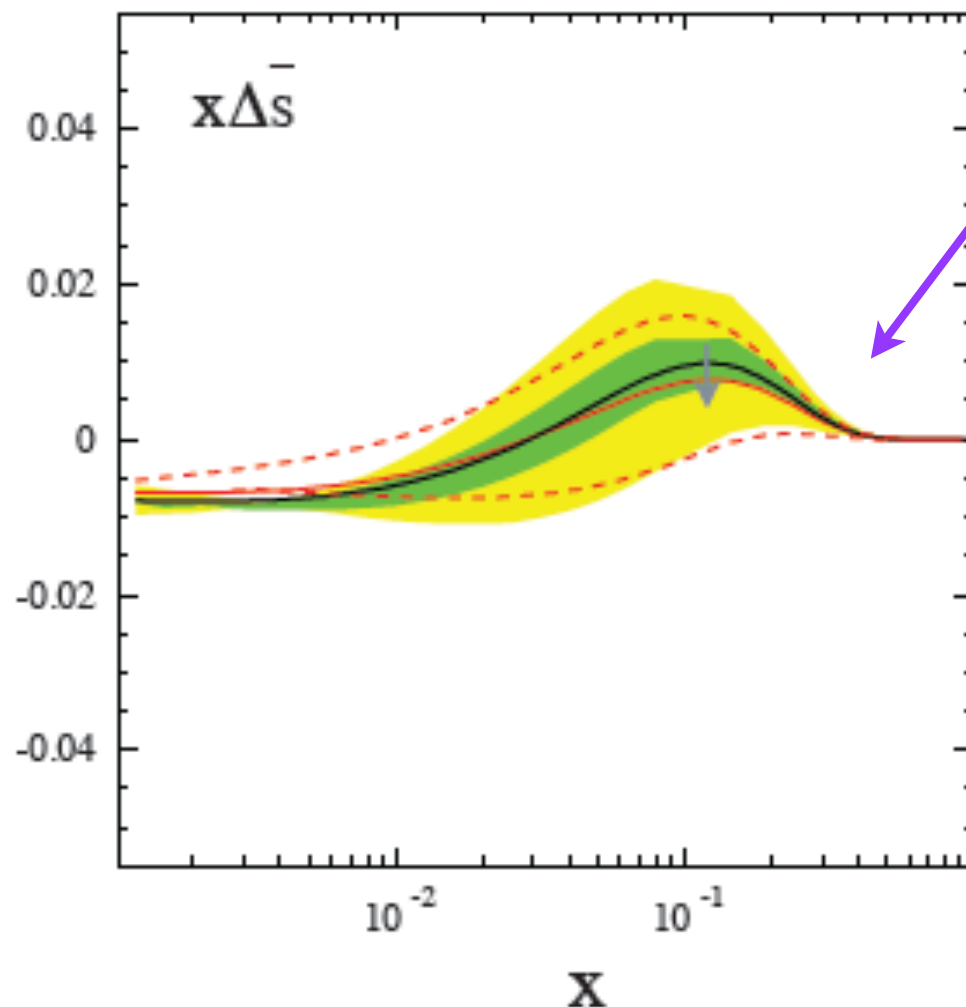
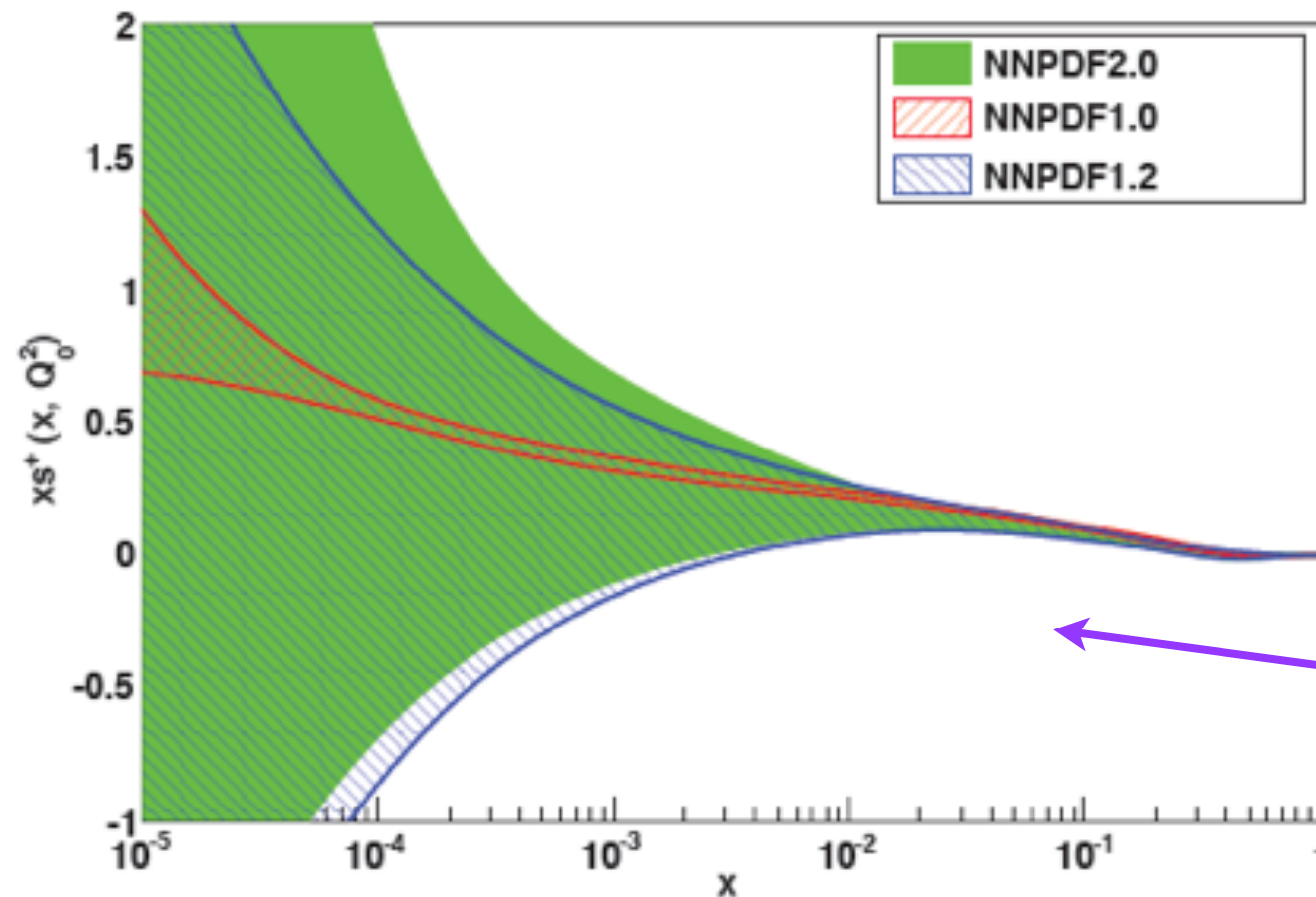
$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x, Q^2)$$



Semi-inclusive DIS



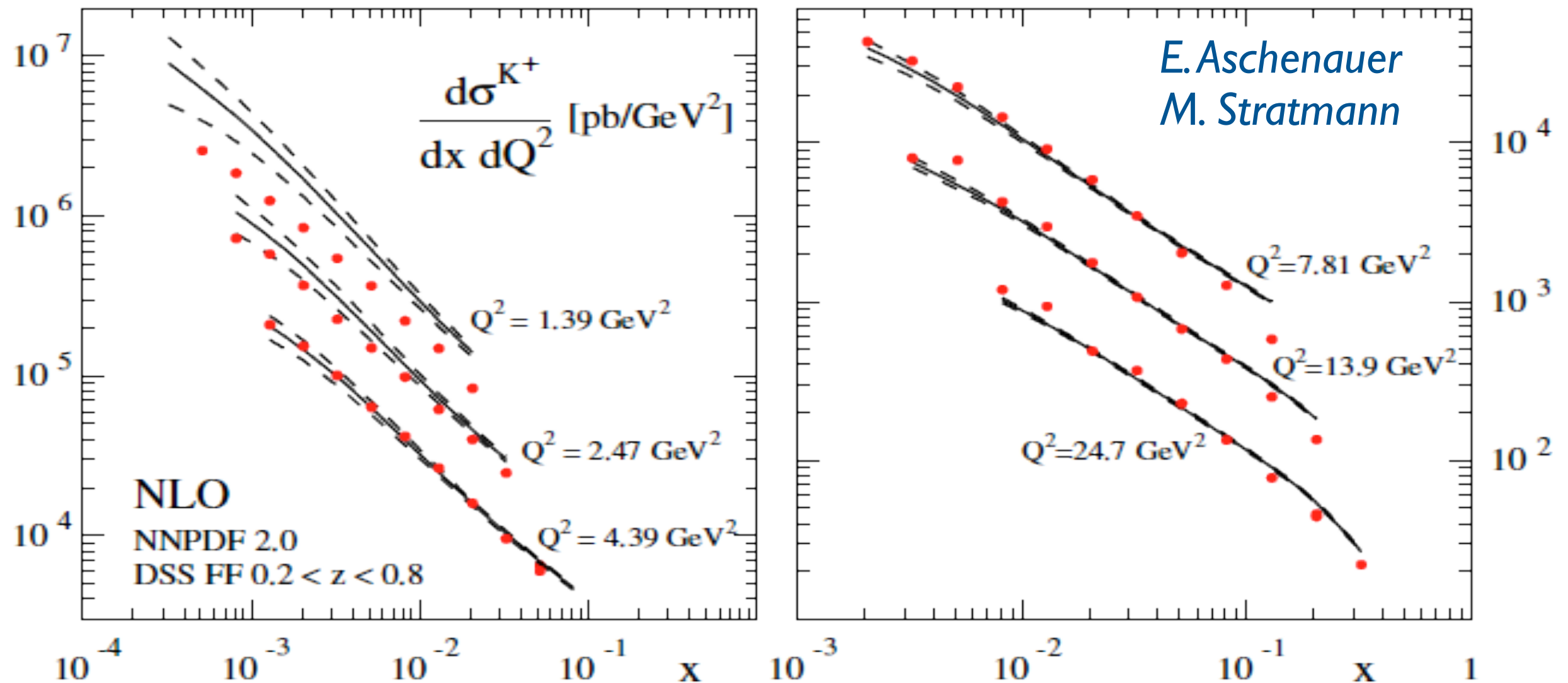
Sea quarks



- Distributions uncertain
- esp. **strange** sea unpolarised & polarised.
- Flavour separation
 - ▶ SIDIS
 - ▶ Variety of hadrons π^+ , π^- , K^+ , K^- ...

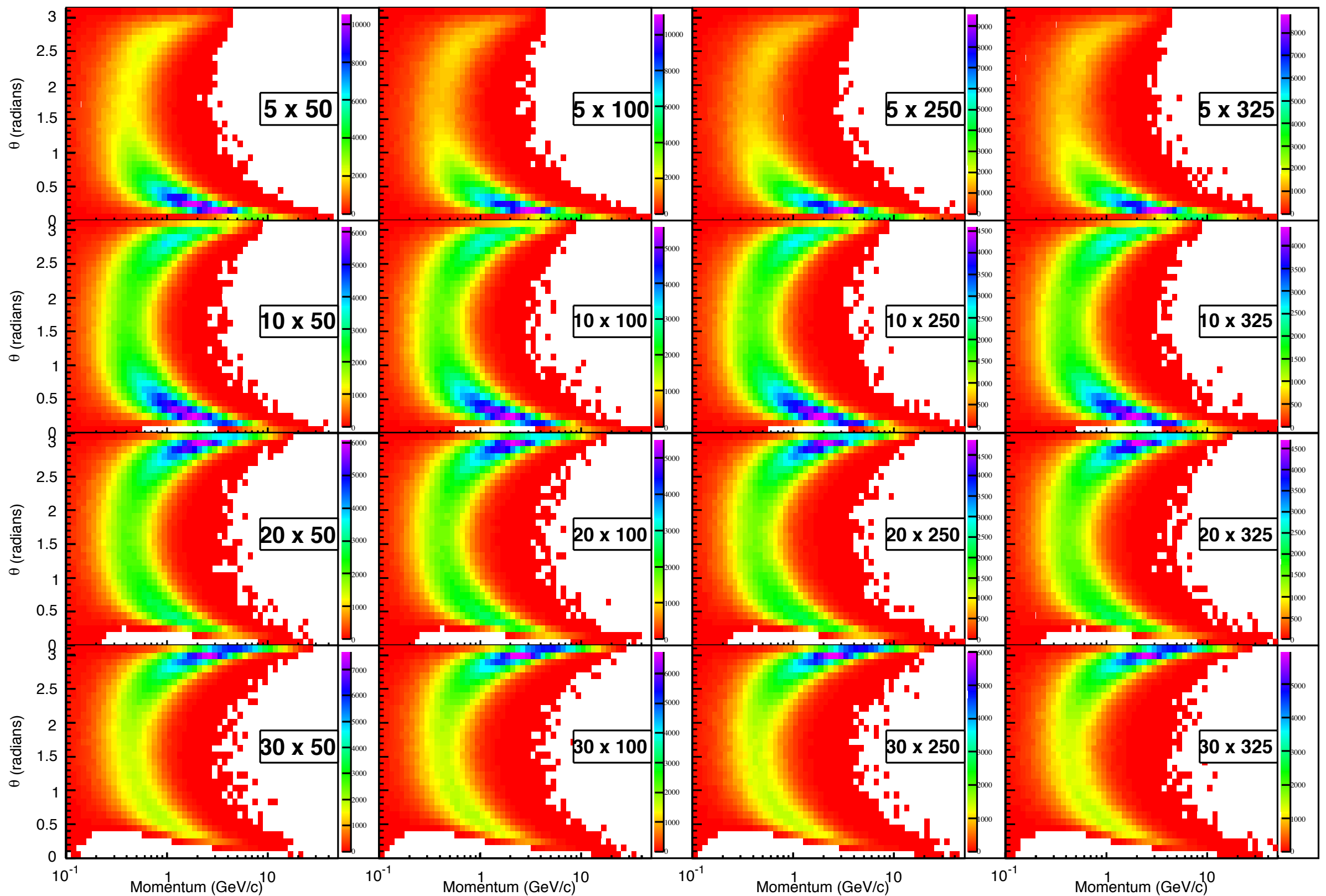
First study

- Can we use MC to simulate psuedodata?
- **PYTHIA** vs. NLO calculation

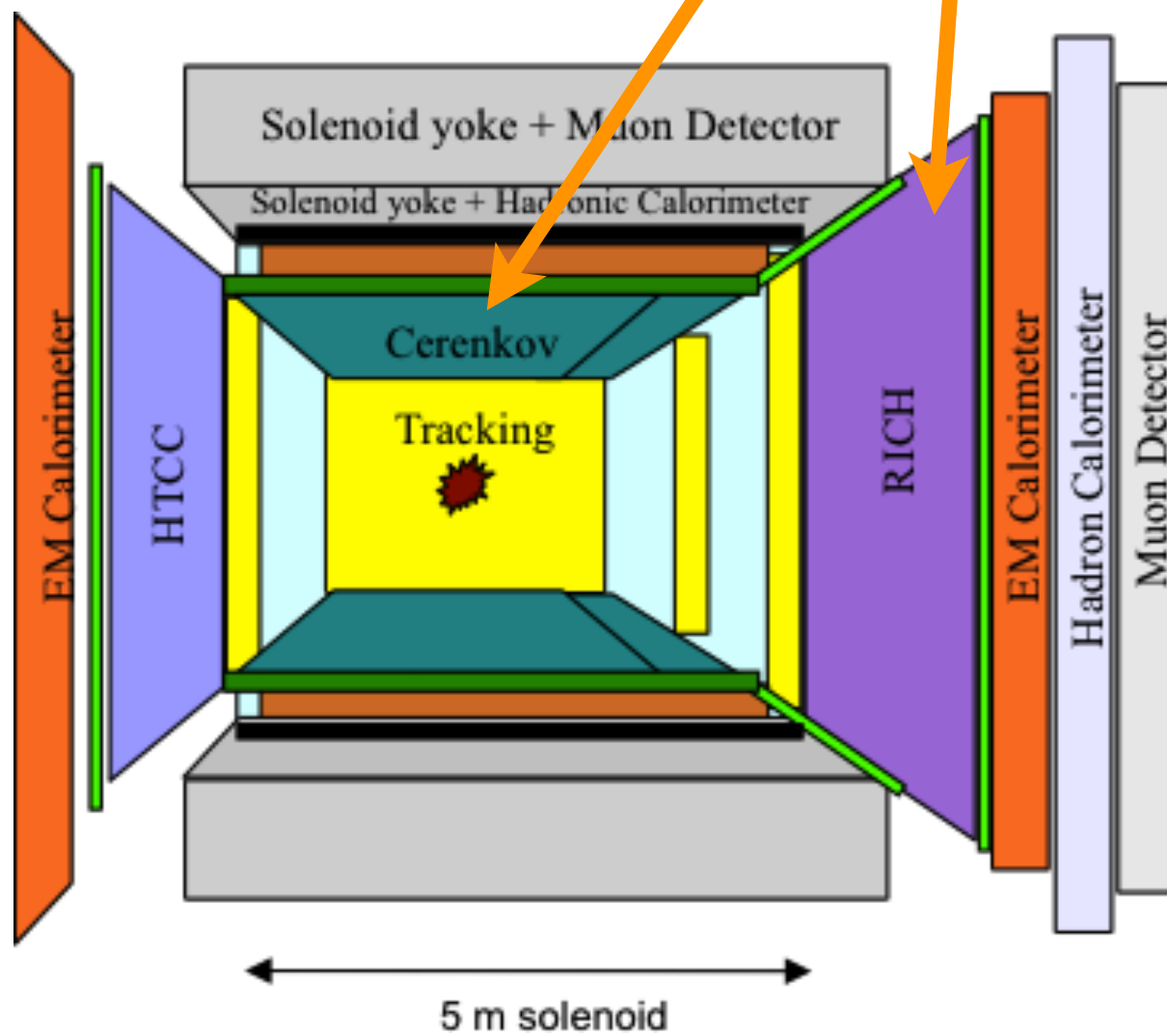


➡ Good agreement

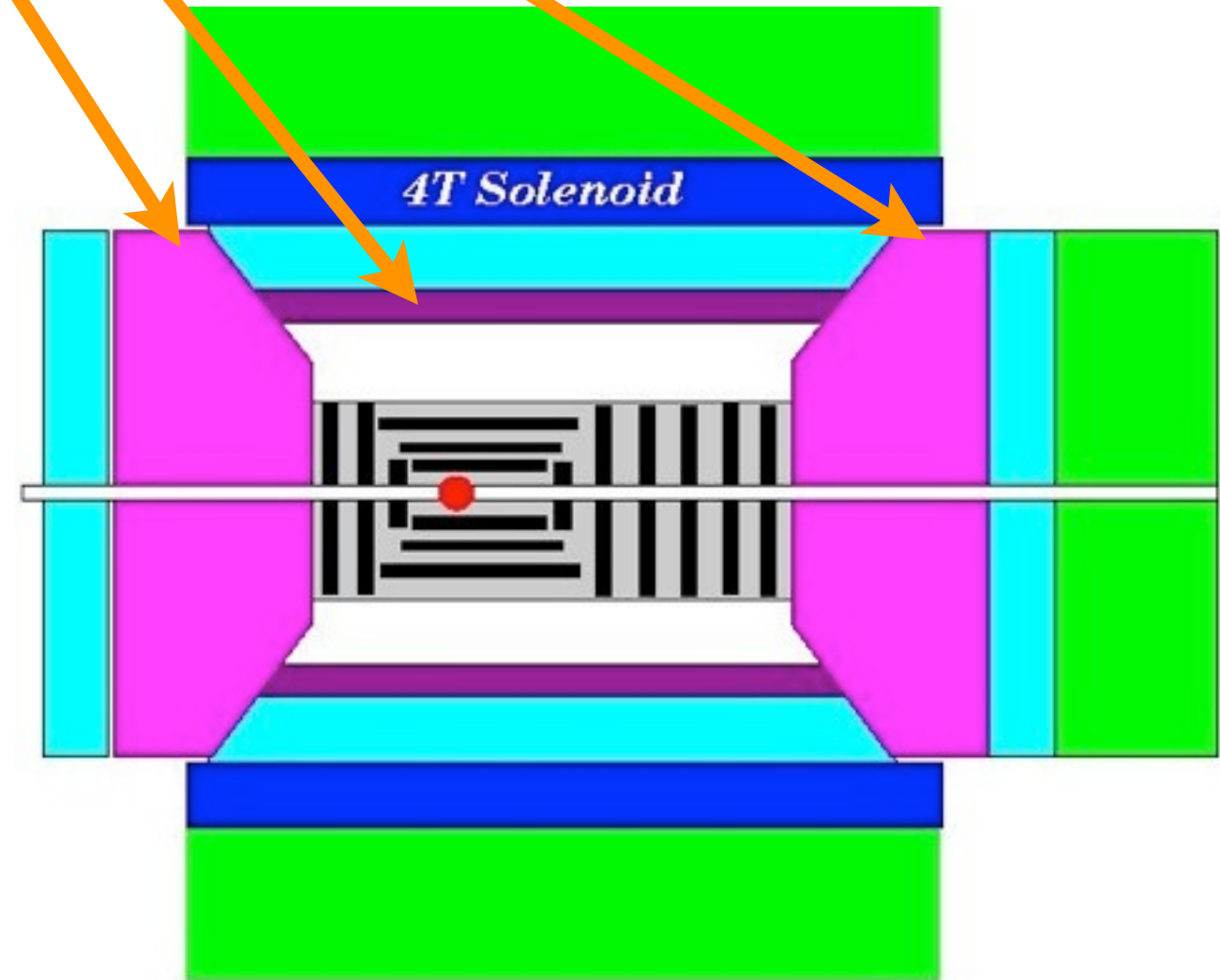
PID coverage: π^\pm



PID



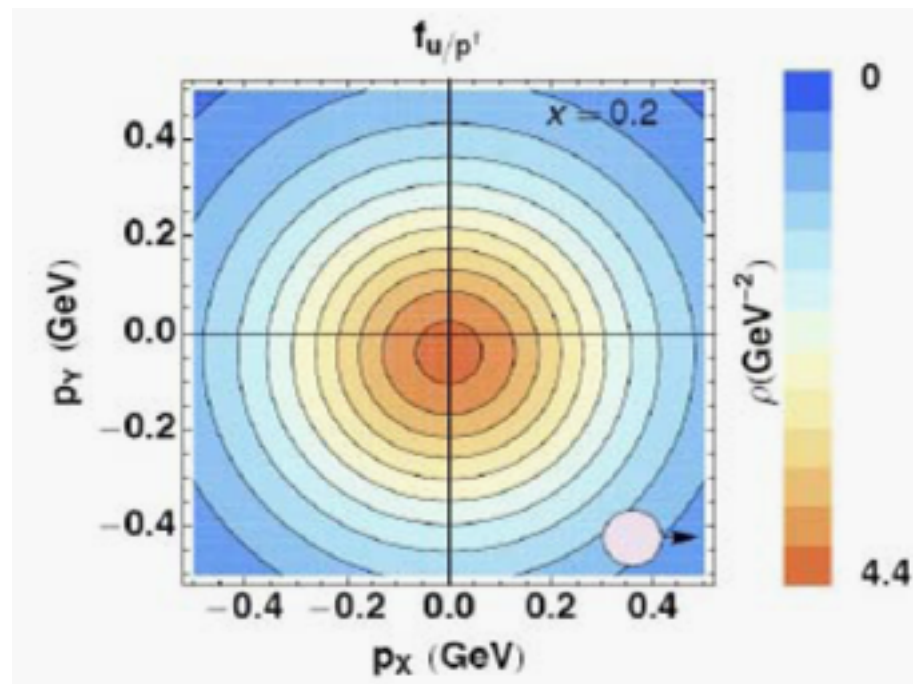
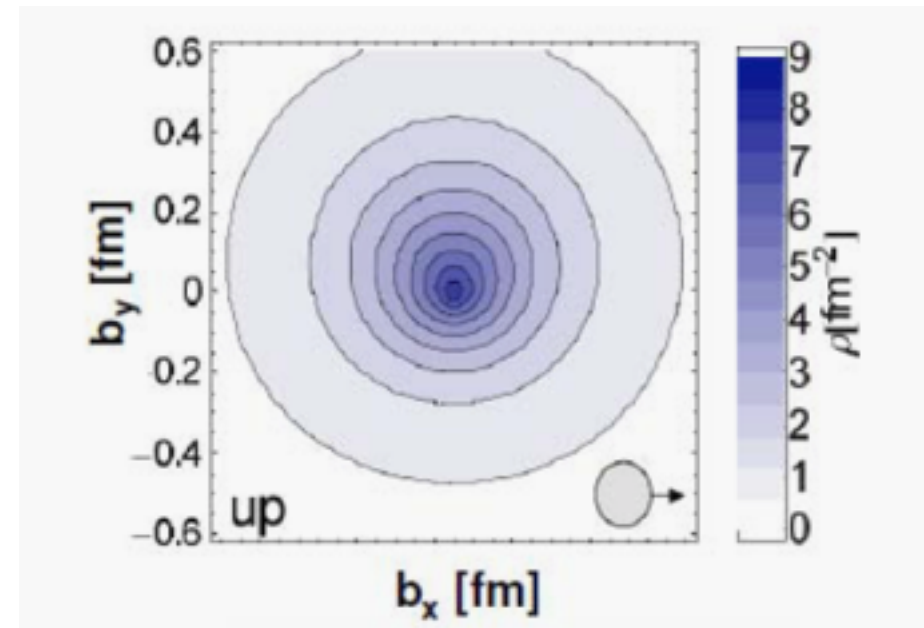
JLab



BNL

Imaging

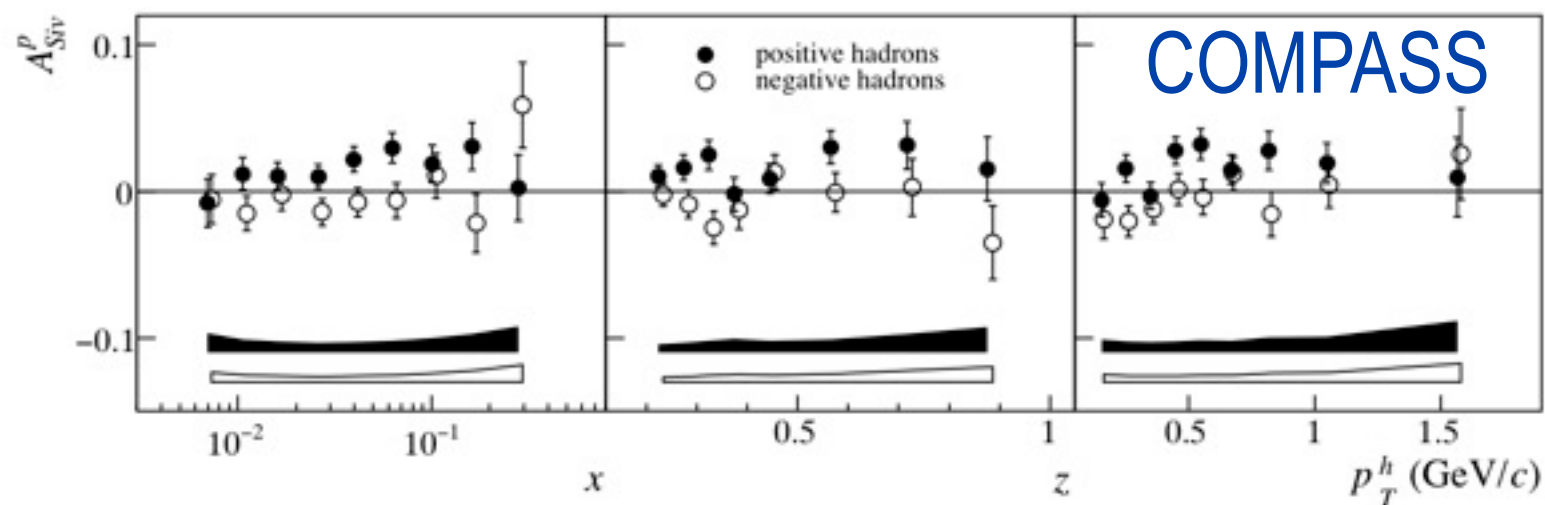
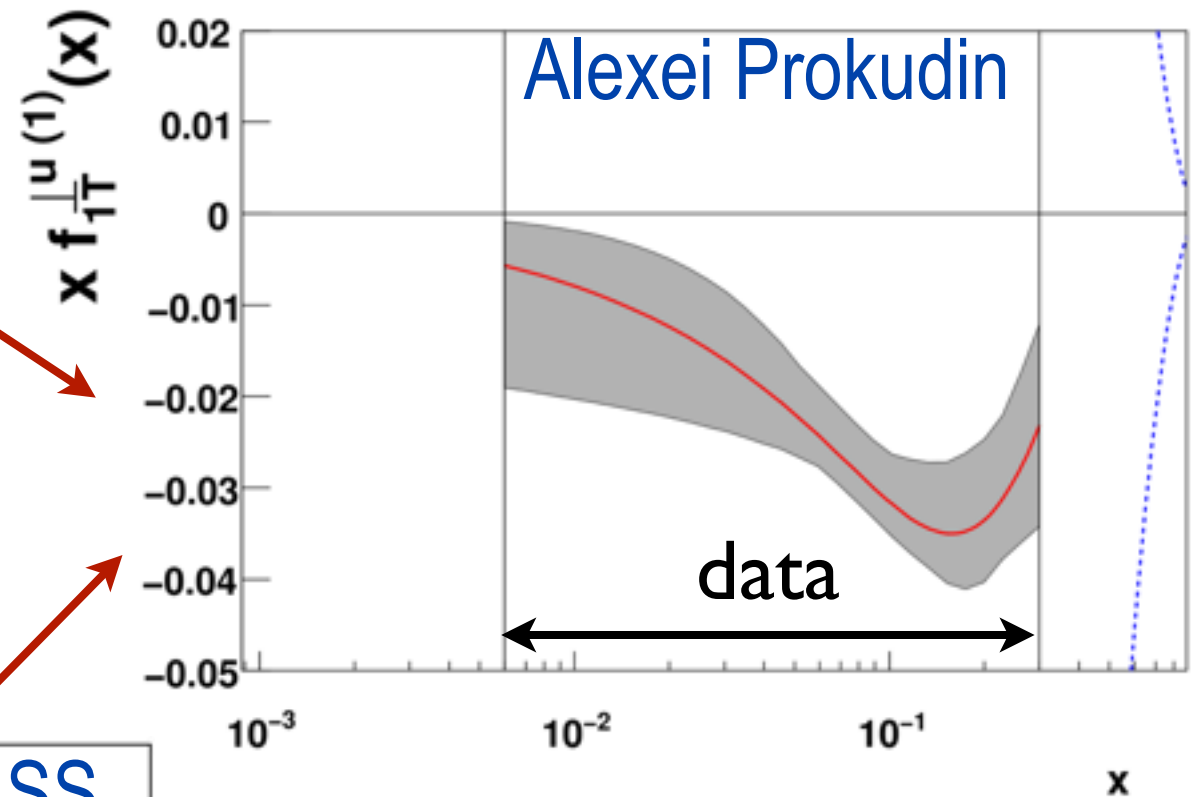
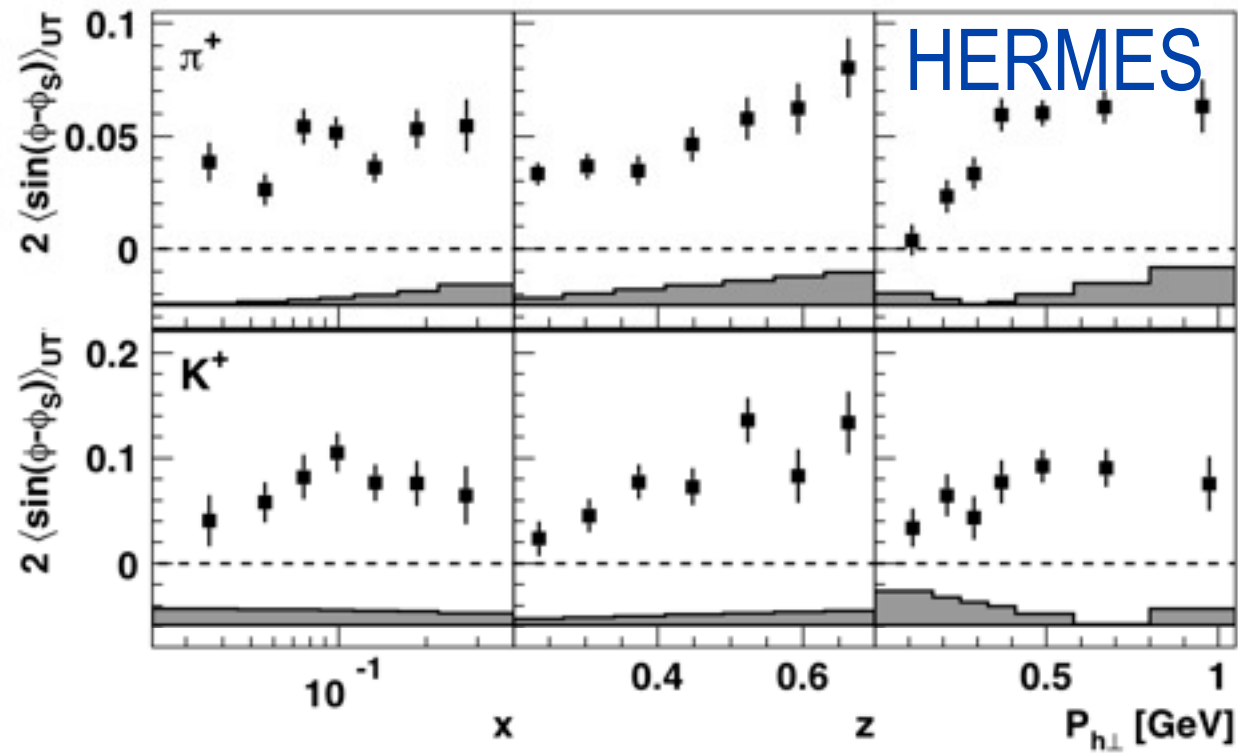
- Generalised parton distributions (GPDs)
 - ▶ transverse **spatial** distribution



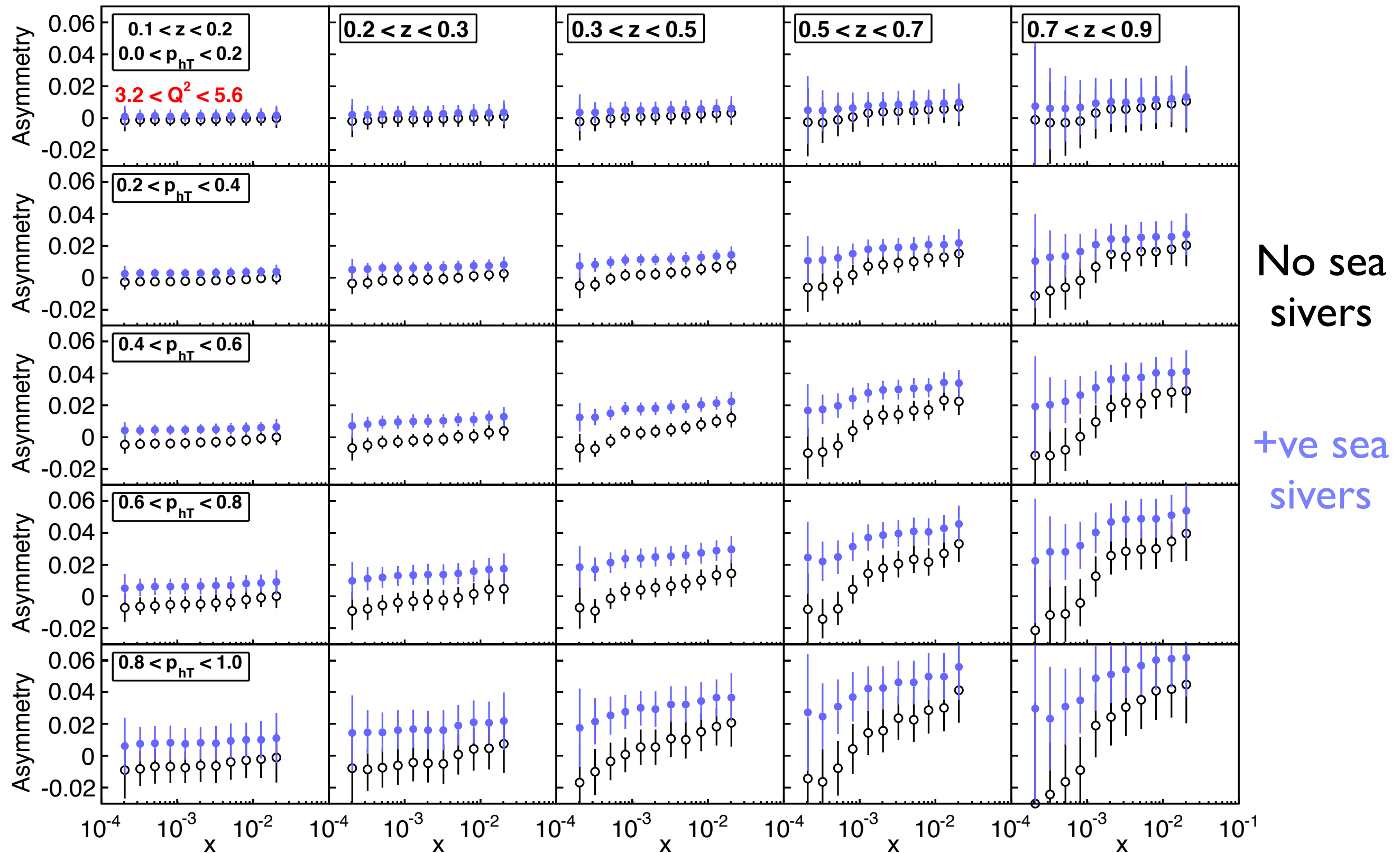
- Transverse-momentum-dependent distribution functions (TMDs)
 - ▶ transverse **momentum** distribution

Sivers distribution

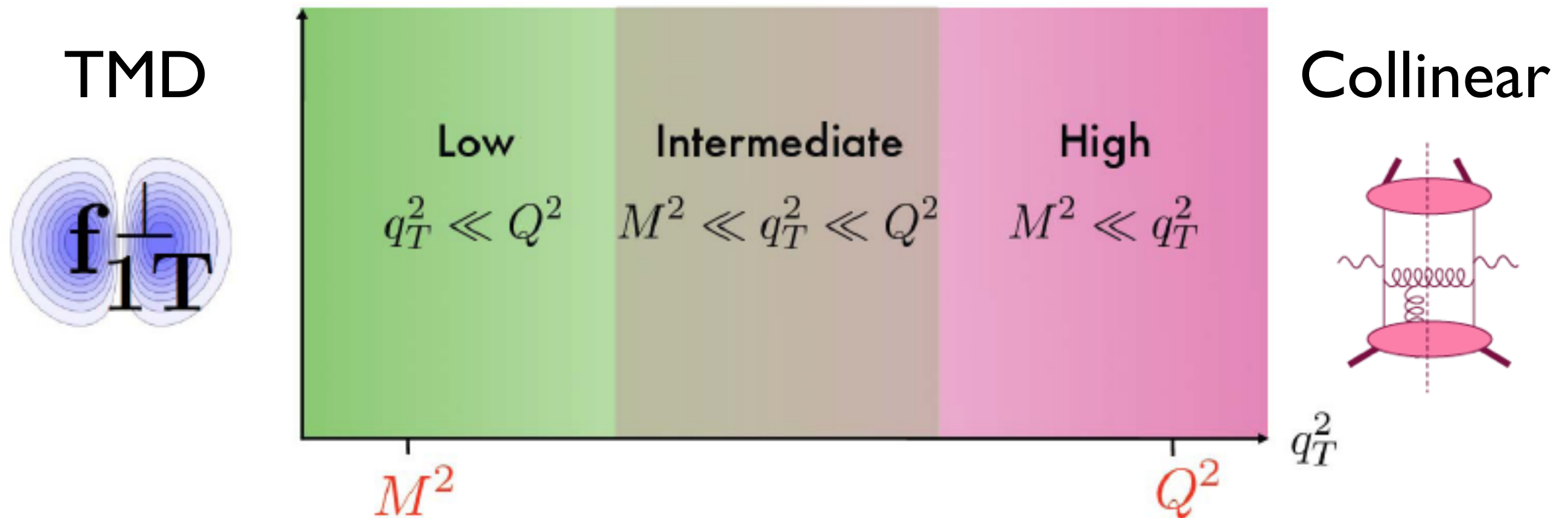
- Correlates q transverse spin & momentum



K^+ 4 fb⁻¹
20 x 250

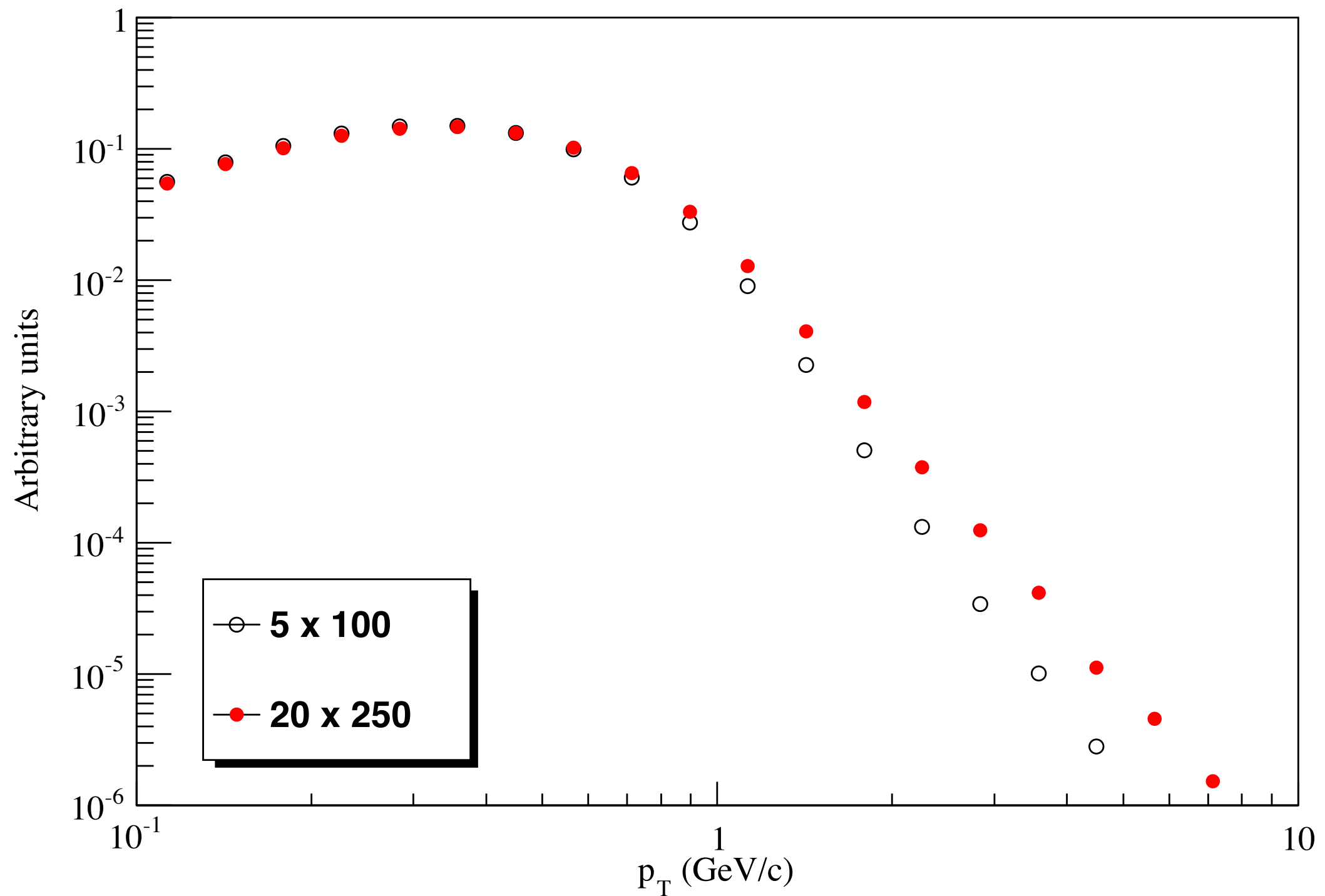


TMD to collinear factorisation: p_T



- Current SIDIS data: low p_T
- EIC: wide p_T range
 - ➔ explore TMD, collinear regime & overlap

PYTHIA: π^\pm p_T



GPDs

- $H(x, \xi, t)$, $E(x, \xi, t)$, $H(\tilde{x}, \xi, t)$, $E(\tilde{x}, \xi, t)$
- Access via hard exclusive processes
- Relate form factors & PDFs

Unpolarised
Polarised

$$\int_{-1}^1 dx H^q(x, \xi, t) = F_1^q(t)$$

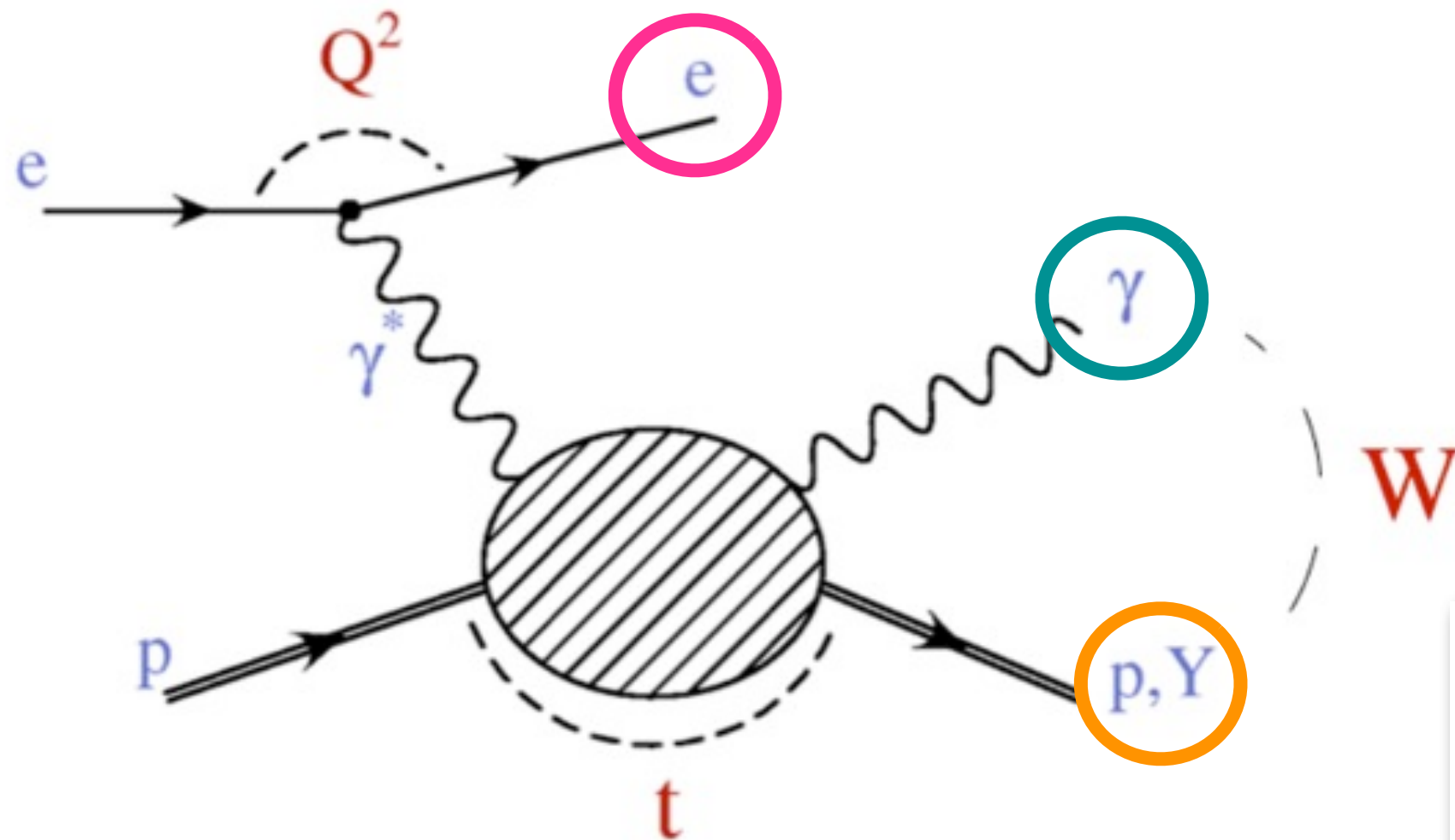
$$H^q(x, 0, 0) = q(x)$$

- Allow:
 - ▶ Spatial imaging: impact parameter, b
 - ▶ Access total angular momentum, J

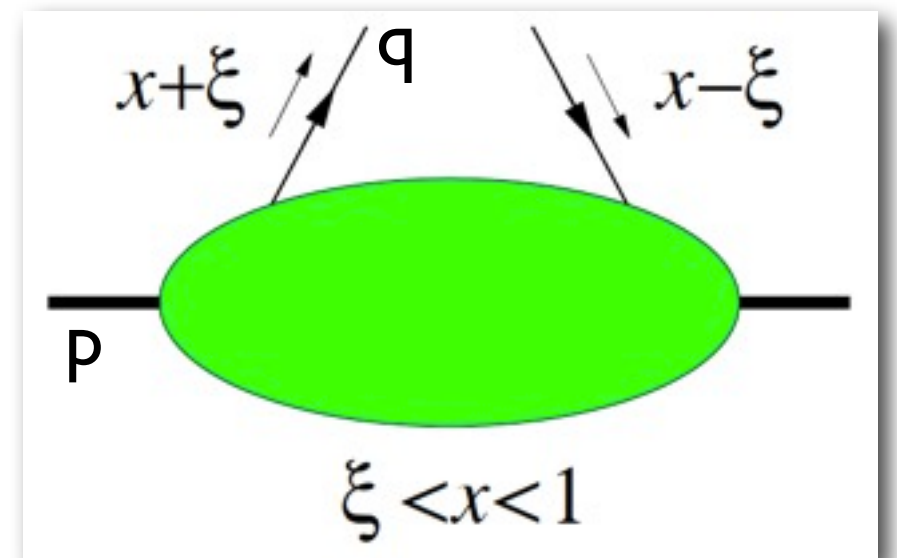
$$J_q^z = \frac{1}{2} \left(\int_{-1}^1 x dx \left(H^q + E^q \right) \right)_{t \rightarrow 0}$$

GPDs

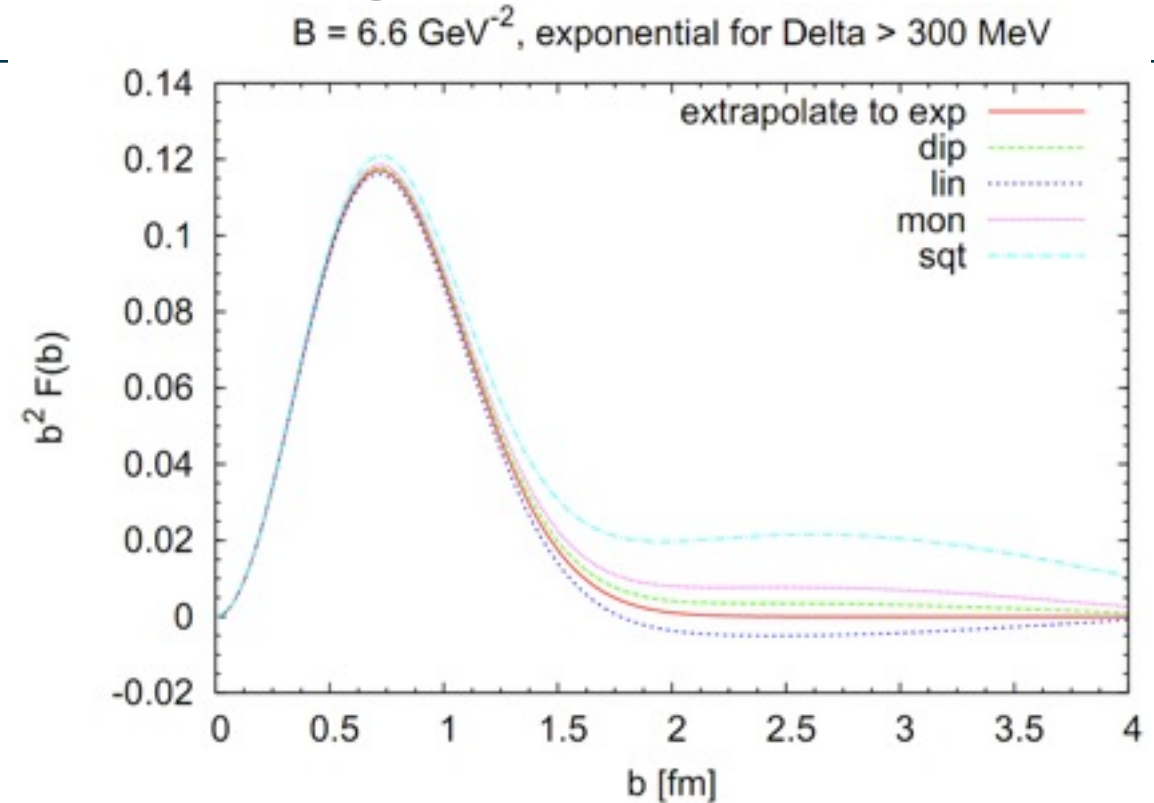
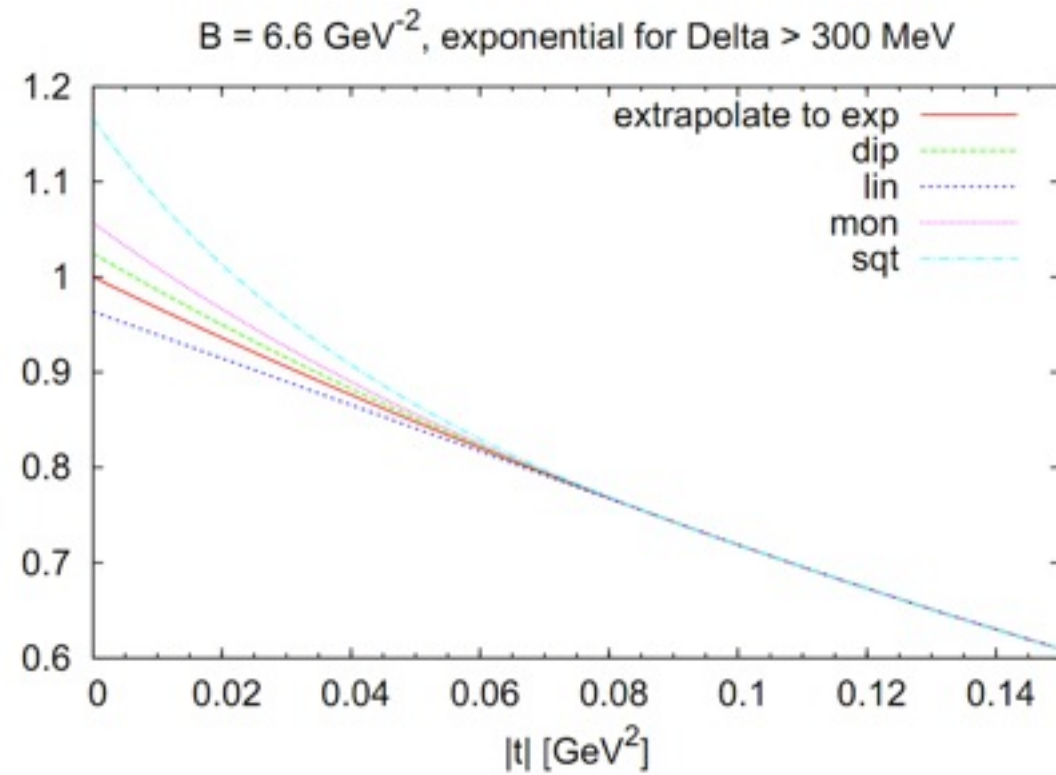
► e.g. deeply virtual Compton scattering:



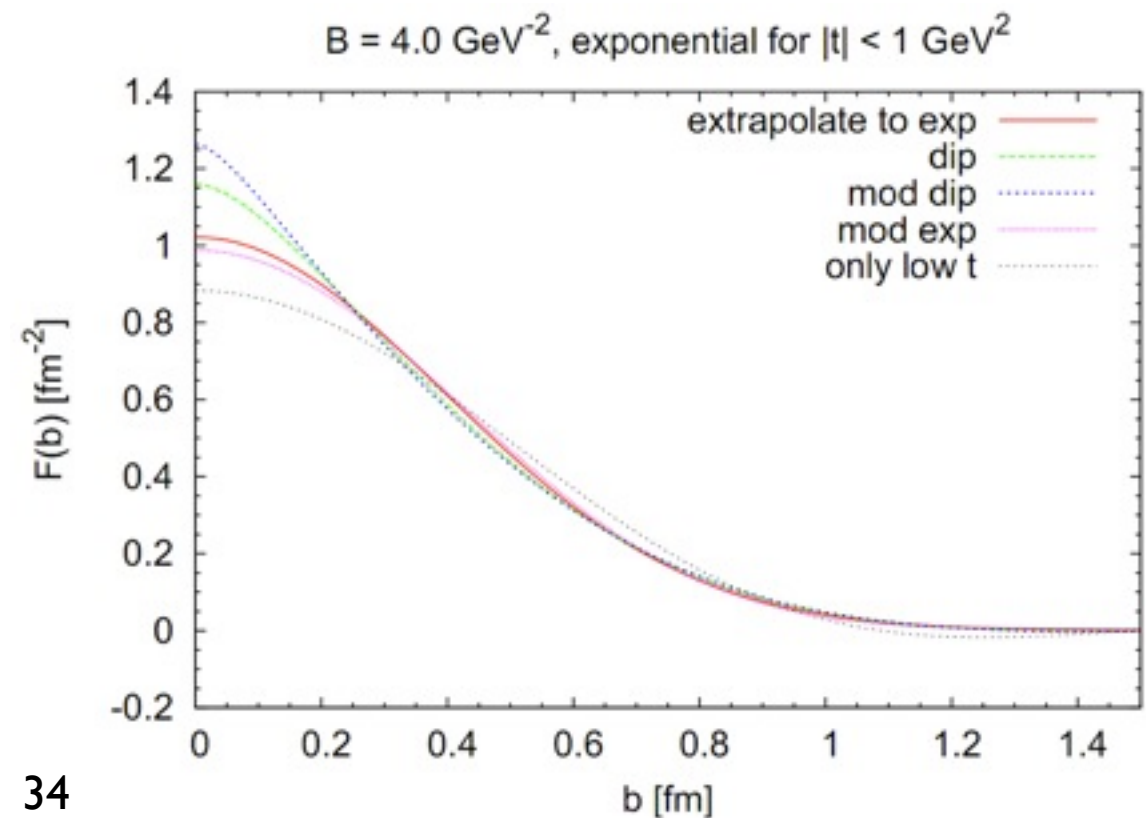
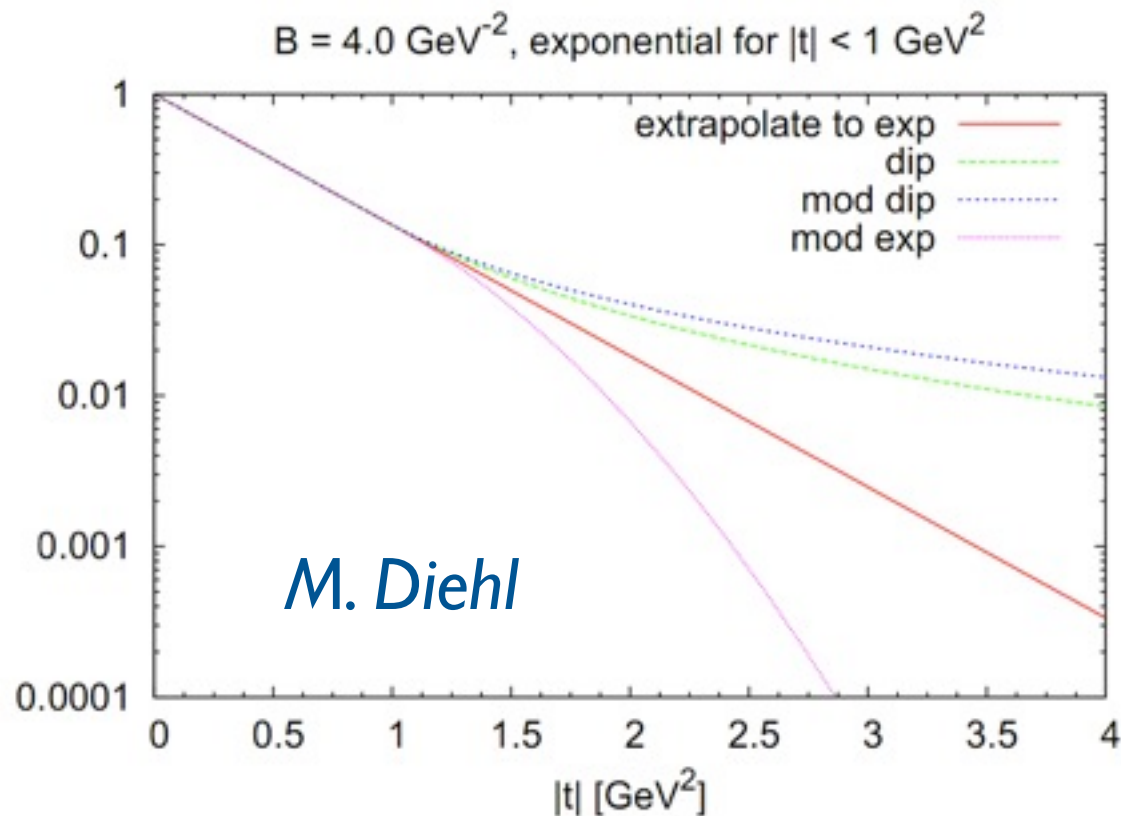
Ideally detect:
scattered electron
real photon
scattered proton



Small t - large b

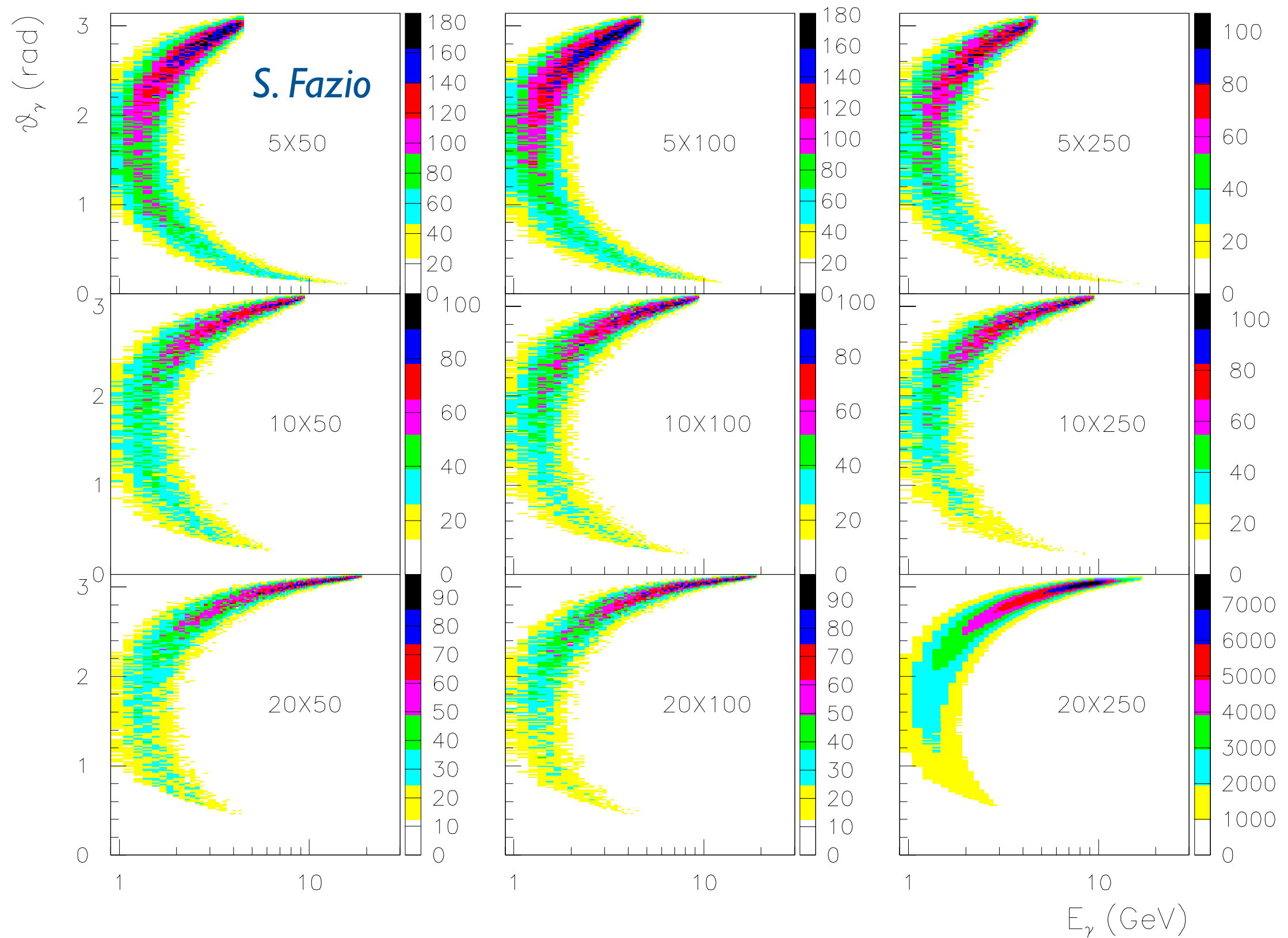


Large t - small b

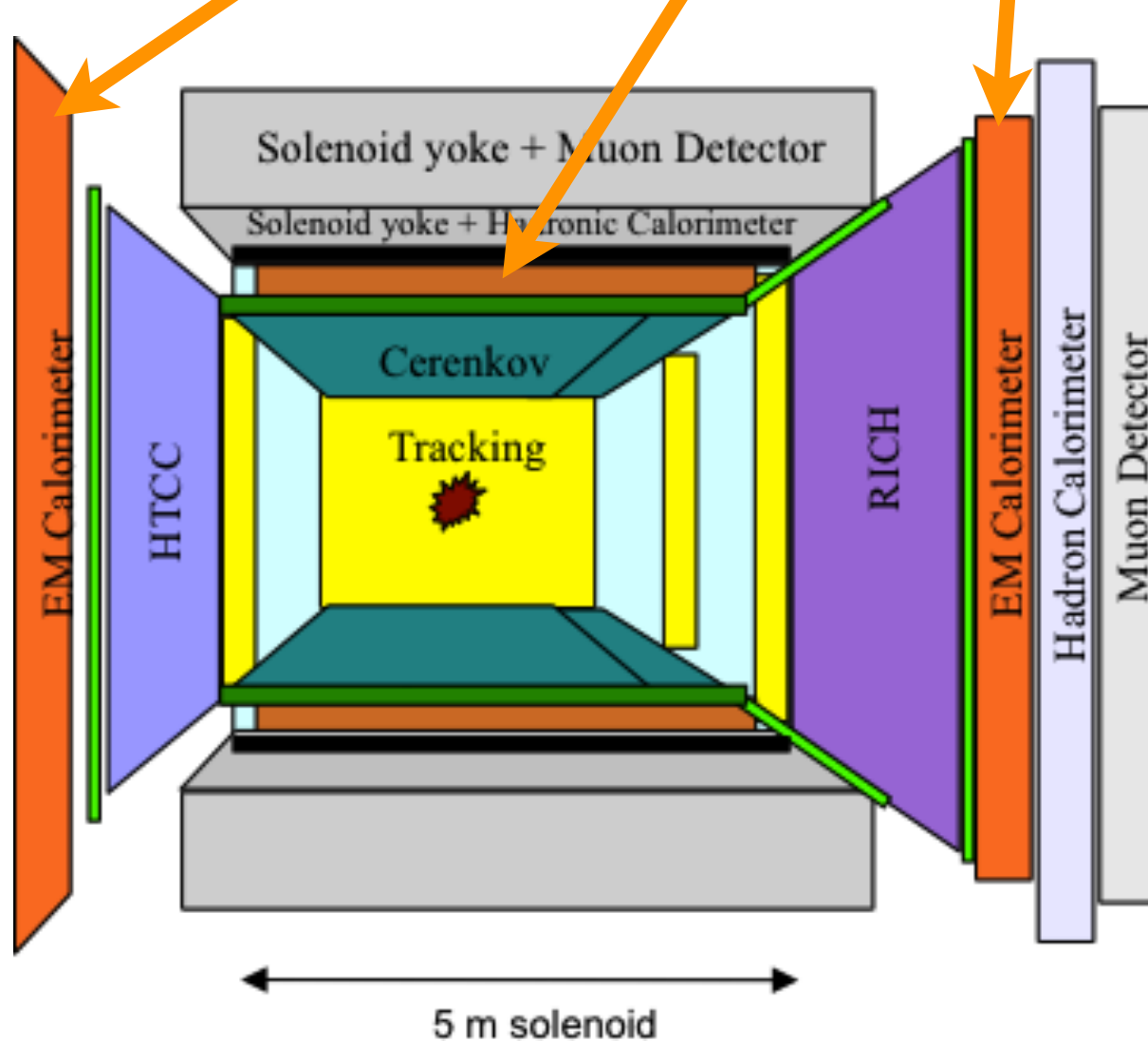


MILOU Monte Carlo generator: γ

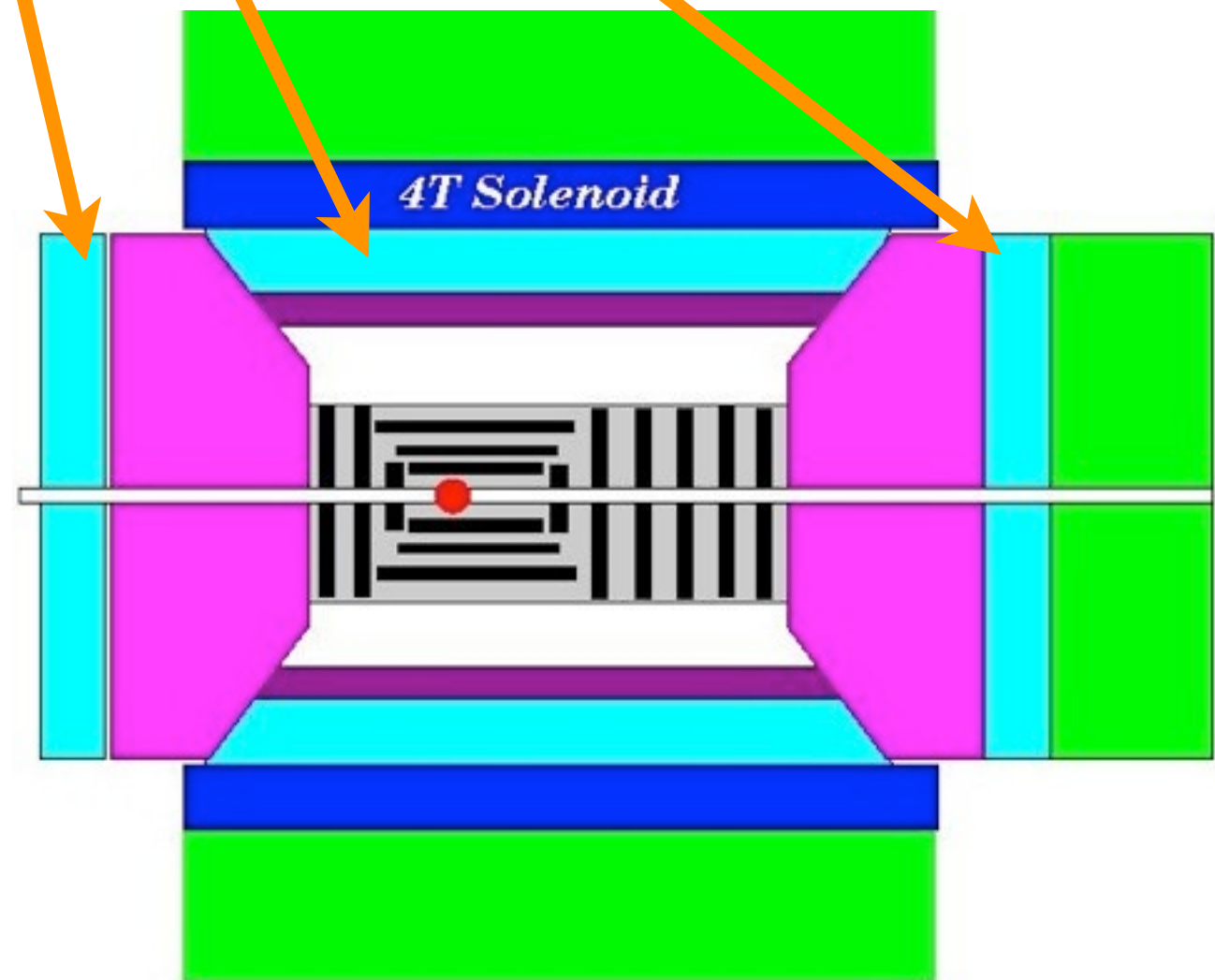
DVCS



EM calorimetry

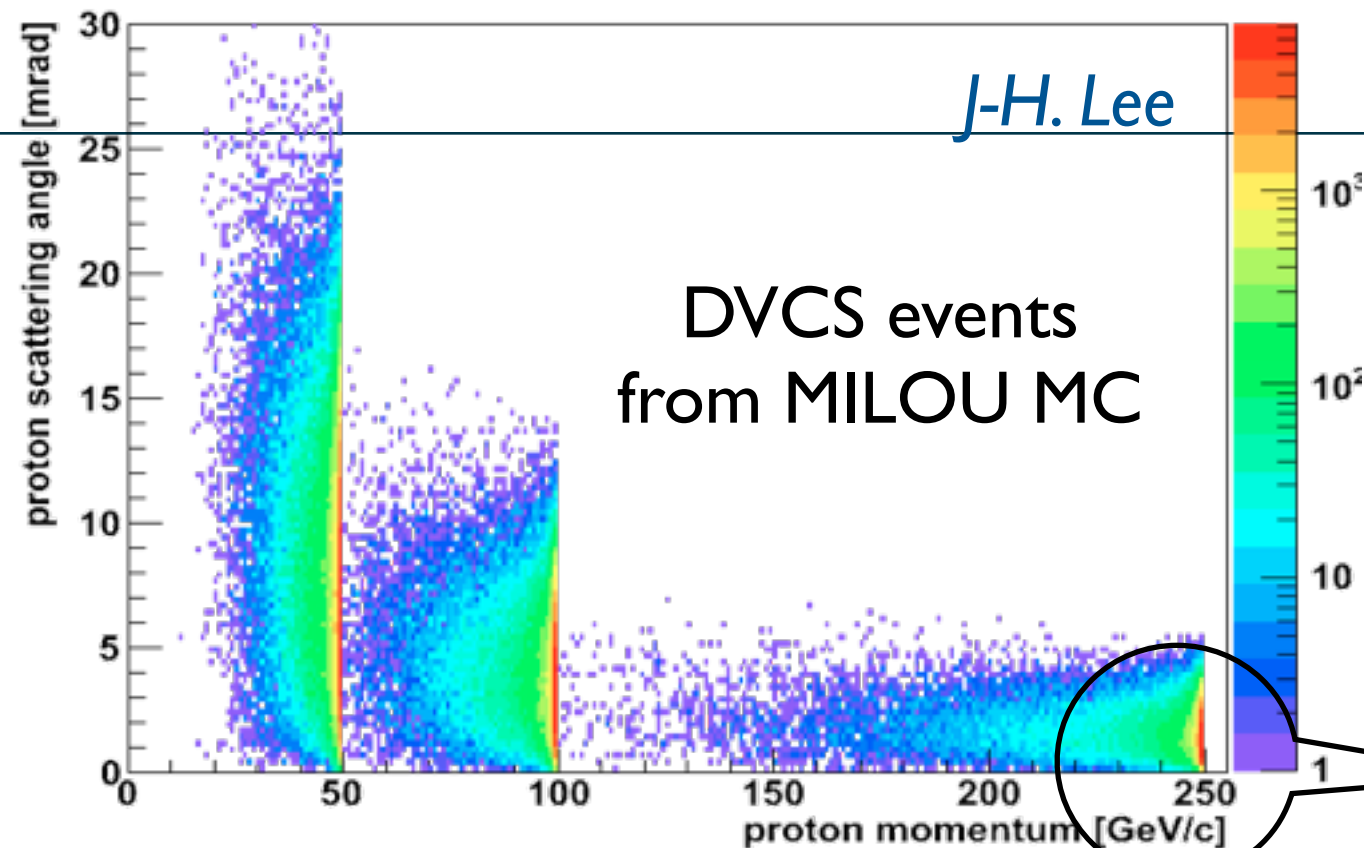


JLab



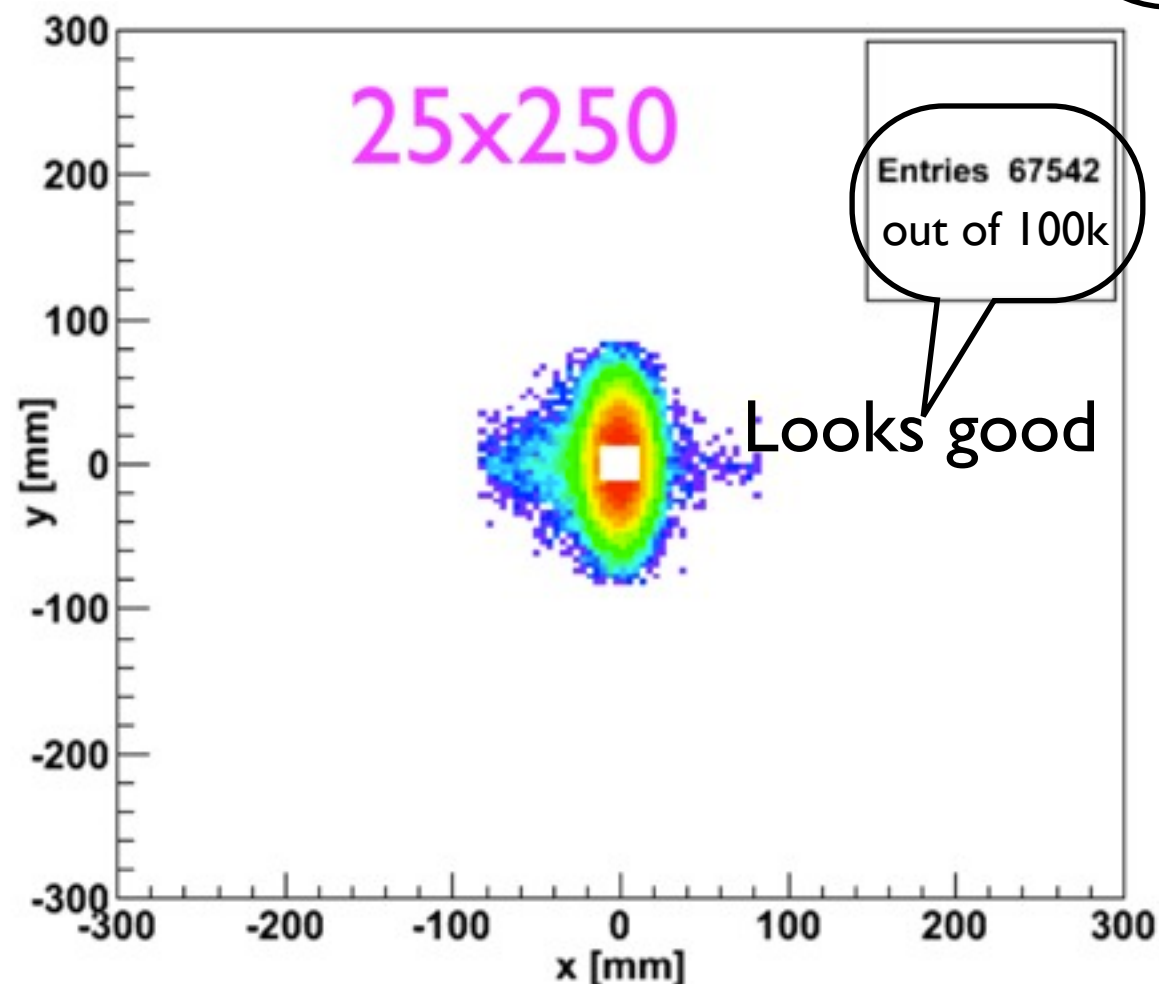
BNL

Proton Detection

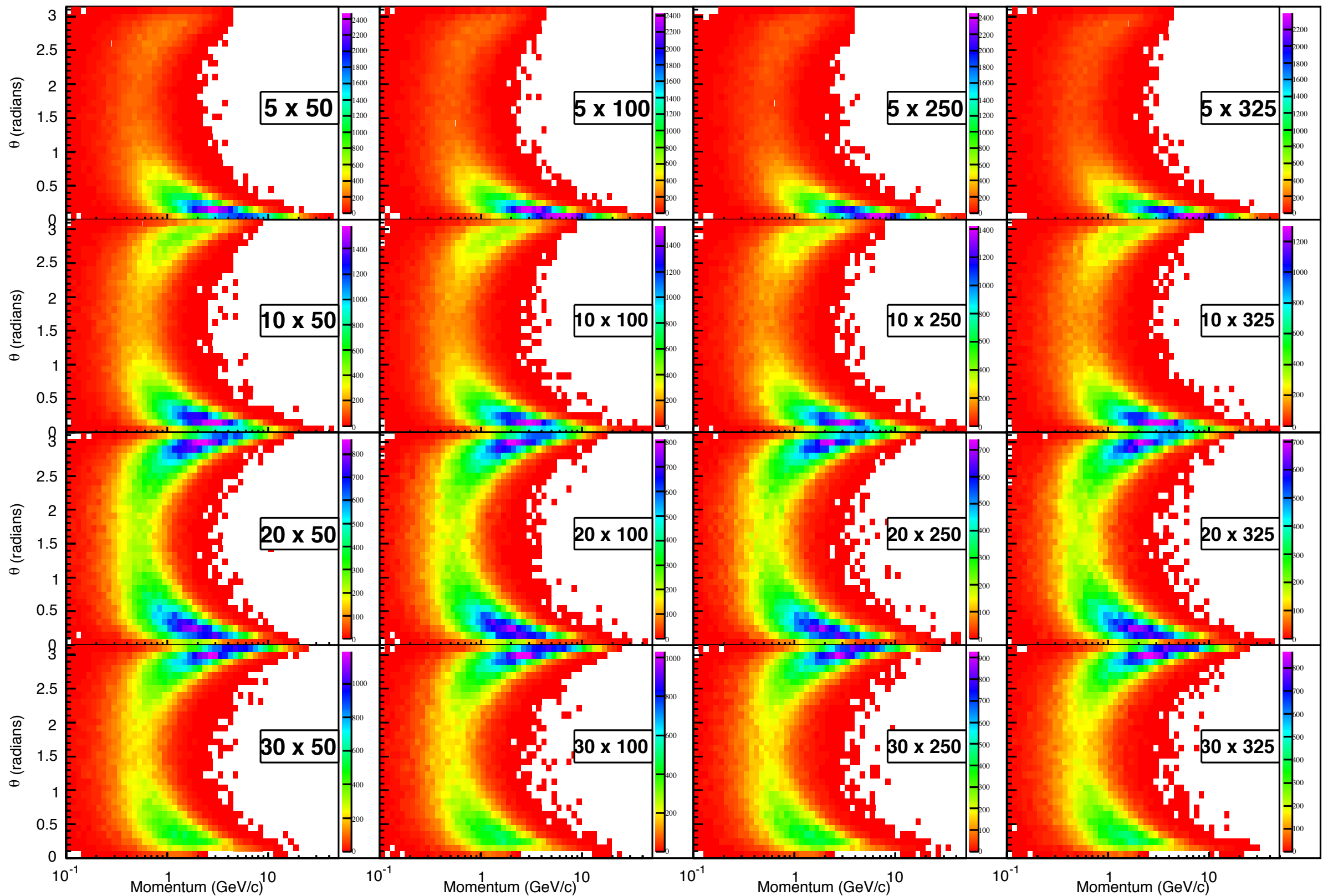


➔ Roman pot detector
needed for proton

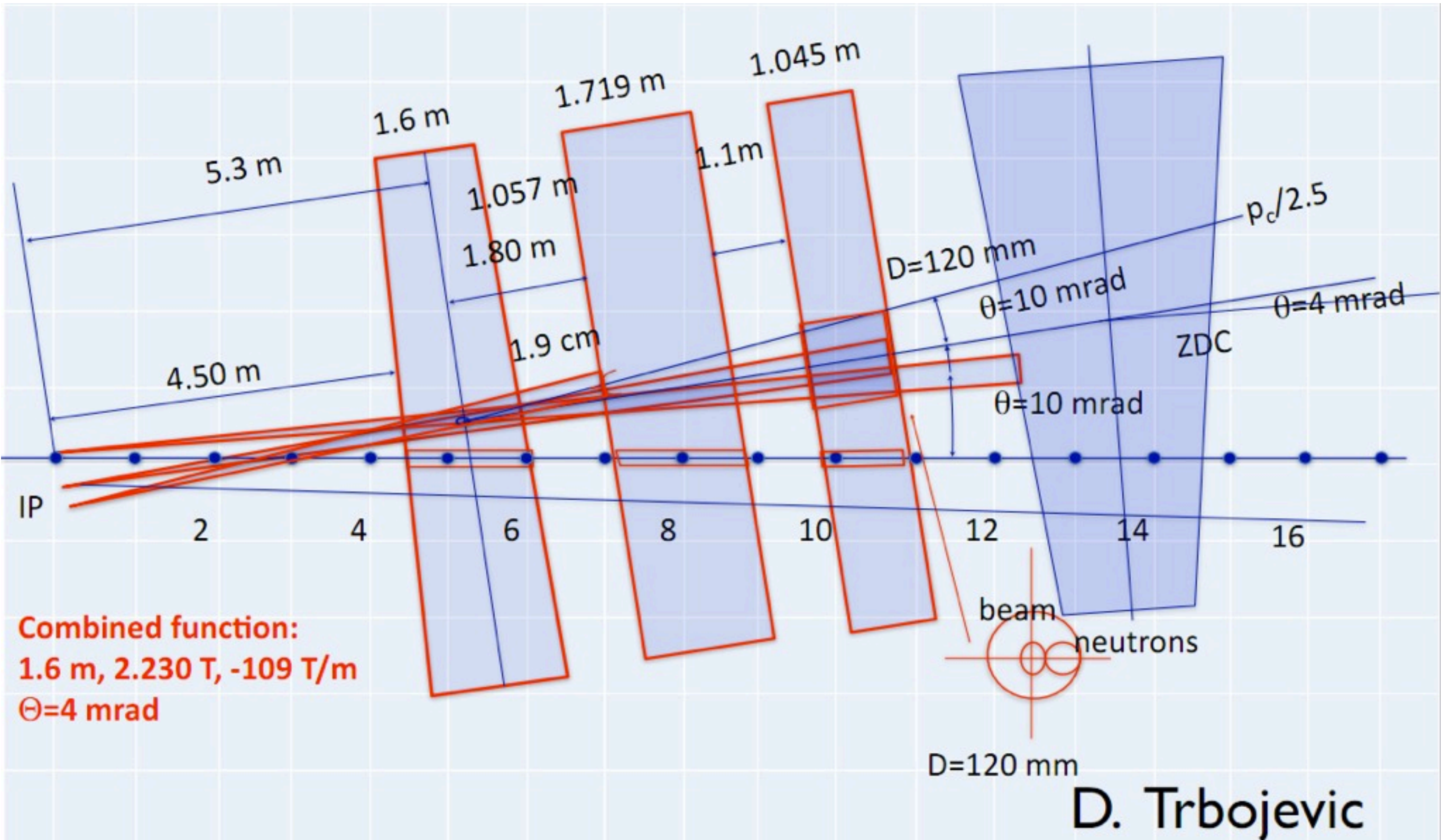
- t acceptance:
 - ▶ beam envelope
 - ▶ magnet apertures



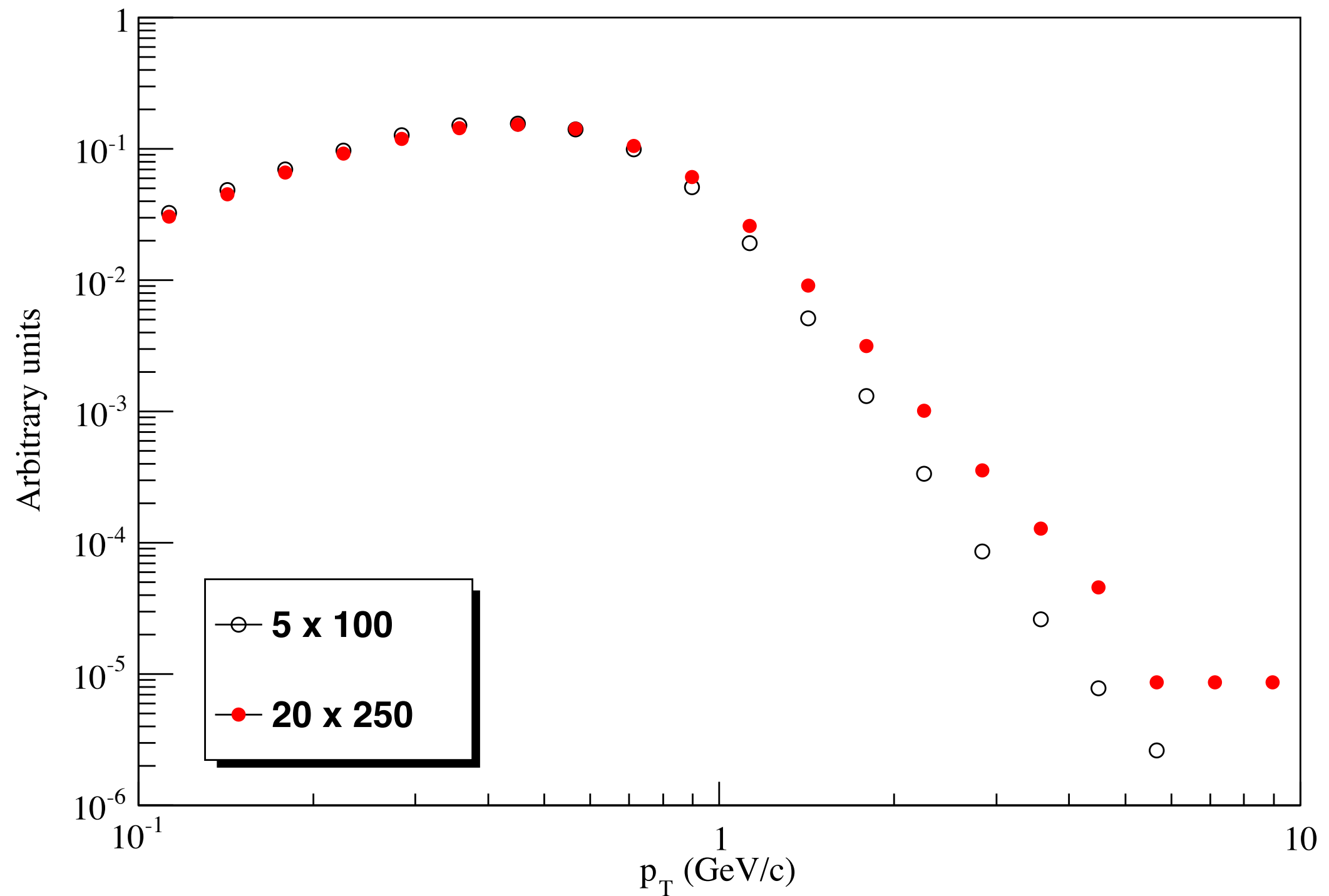
PID coverage: K^\pm

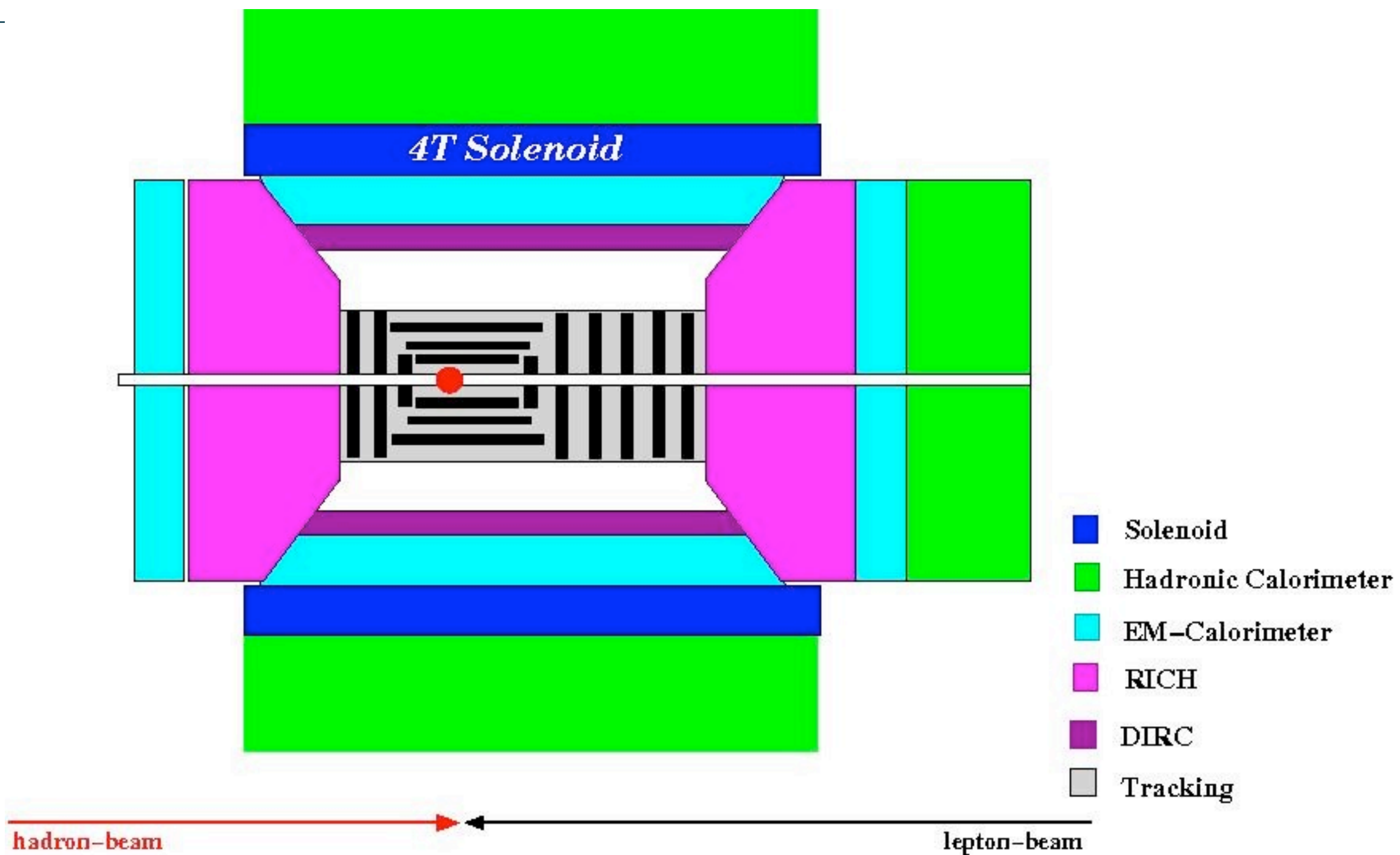


eRHIC interaction region

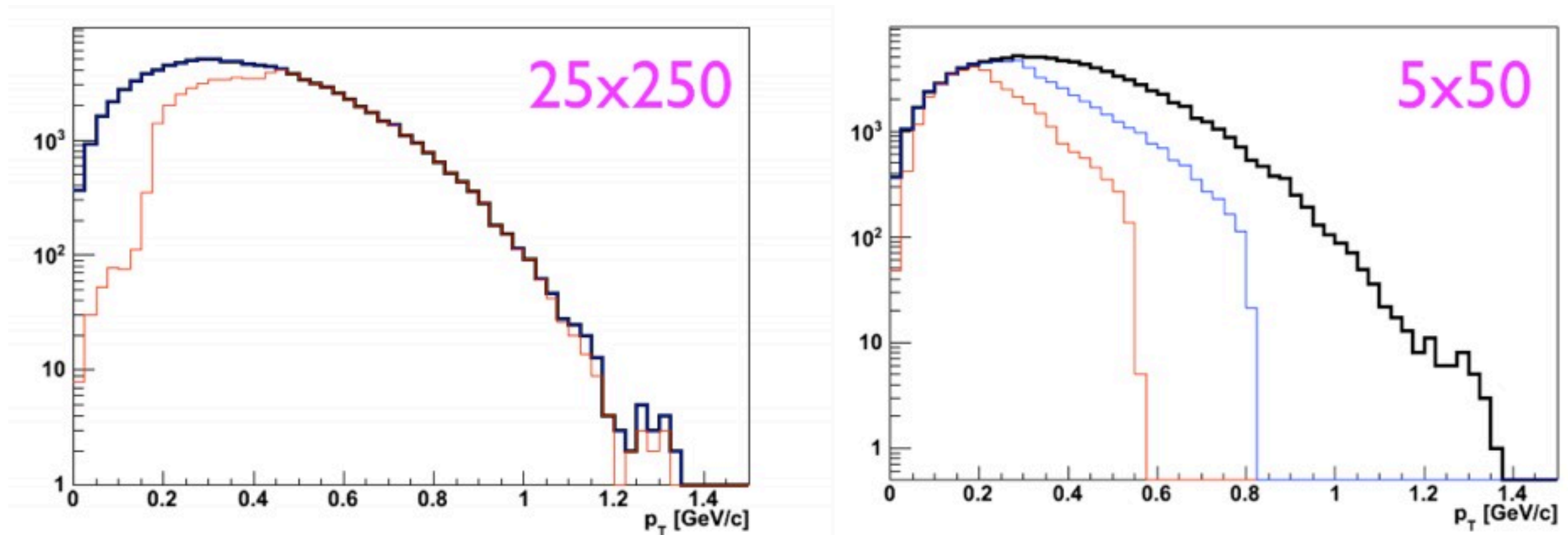


PYTHIA: K^\pm p_T



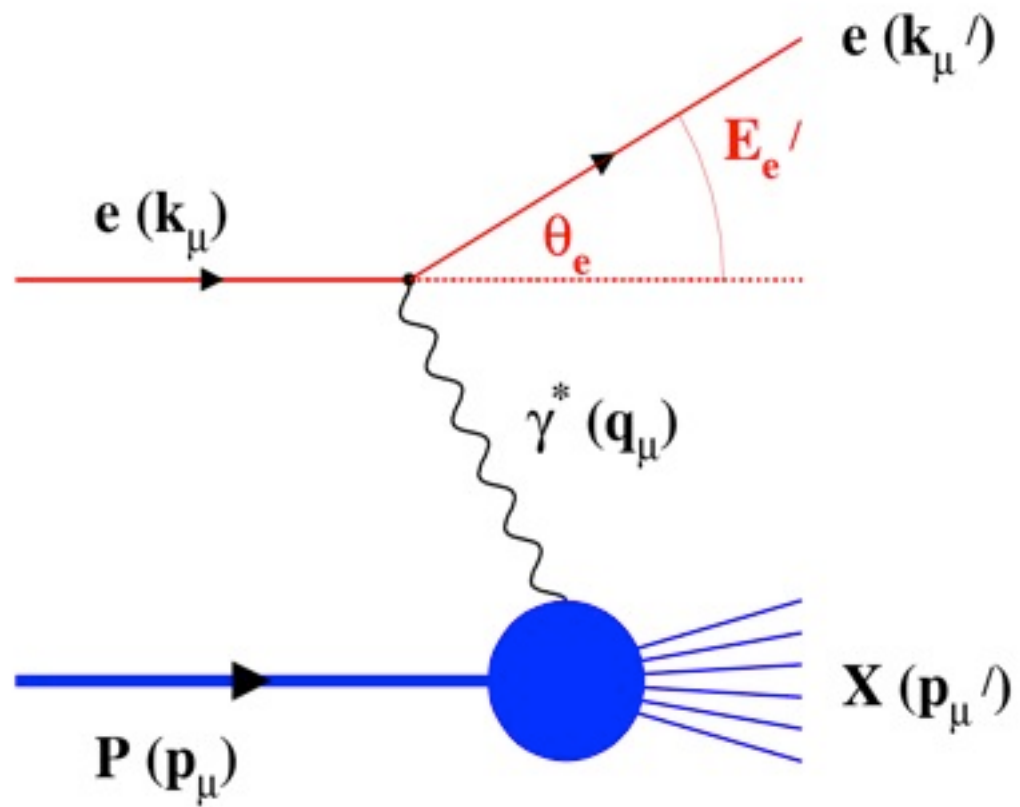


Roman pot p_T acceptance

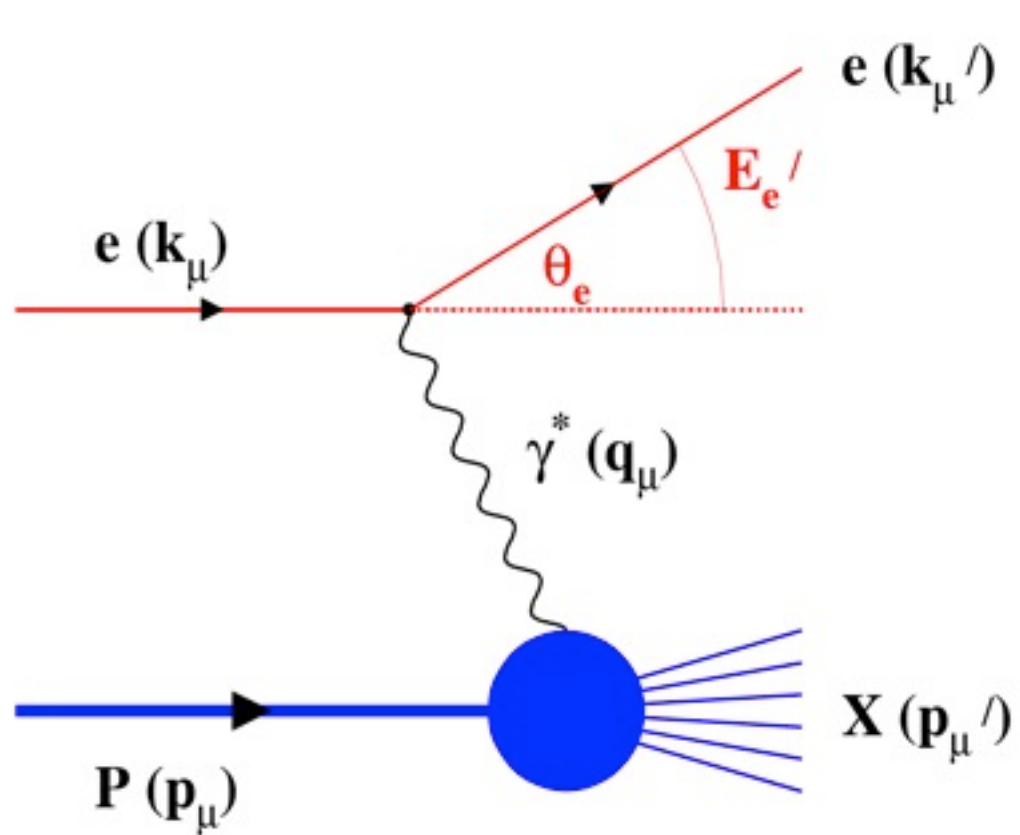


- Generated
- Quad aperture limited
- RP (at 20m) accepted

DIS Kinematics



DIS Kinematics

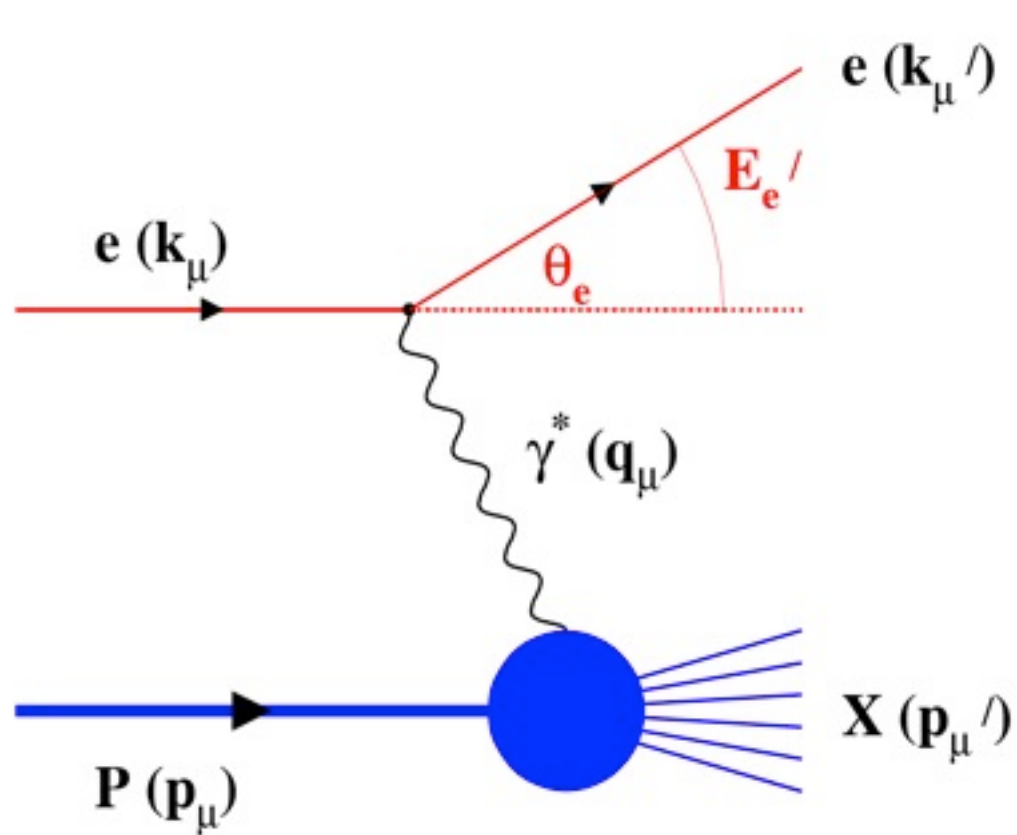


$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of
resolution
power or
"Virtuality"

DIS Kinematics



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

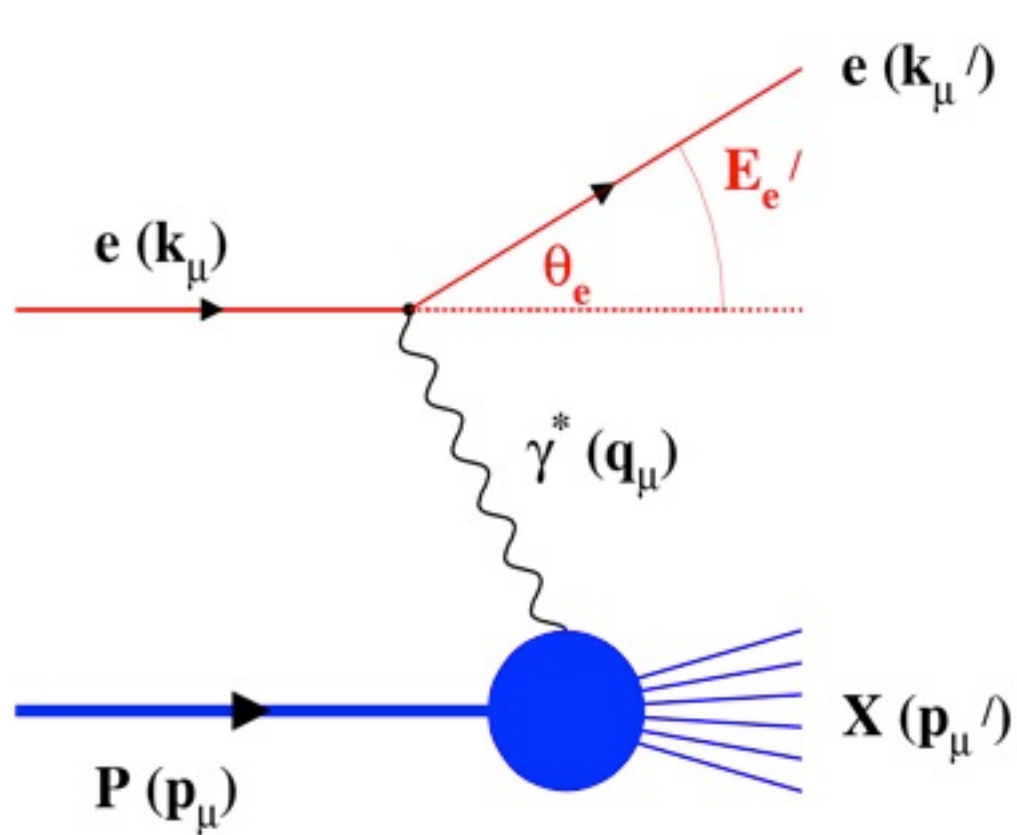
Measure of resolution power or "Virtuality"

$$Q^2 = 4E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

$$y = \frac{pq}{pk} = 1 - \frac{E_{e'}}{E_e} \cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

DIS Kinematics



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power or "Virtuality"

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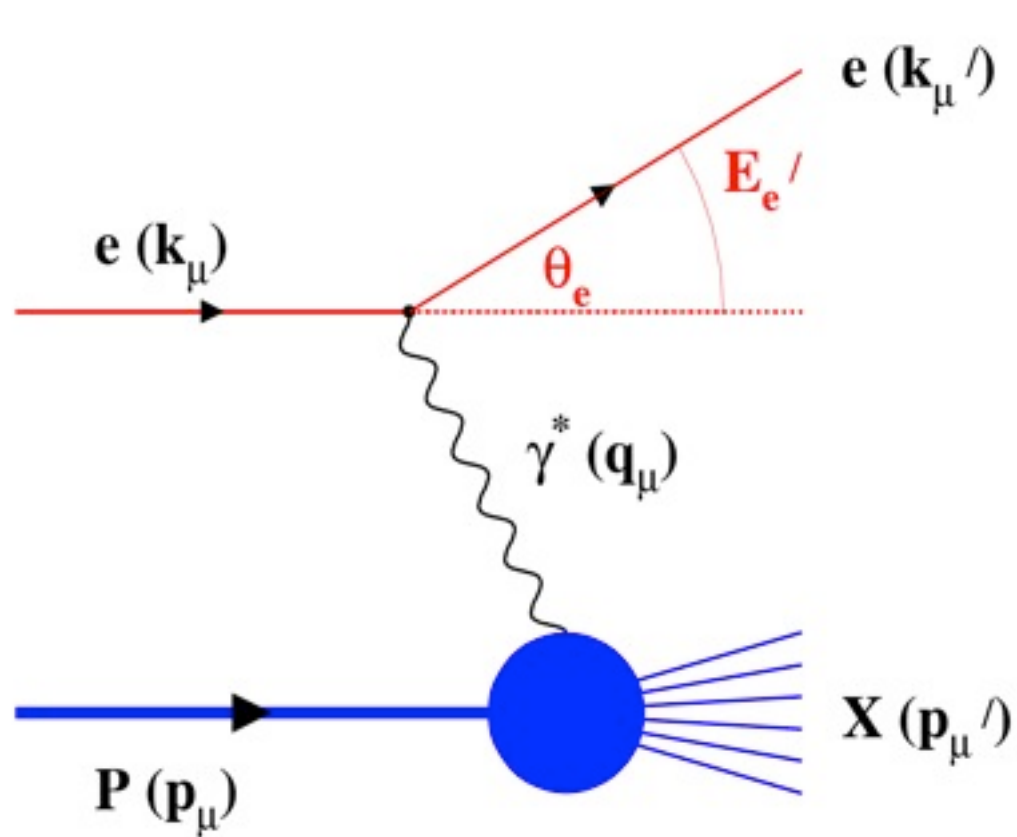
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Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

DIS Kinematics



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Measure of resolution power or "Virtuality"

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